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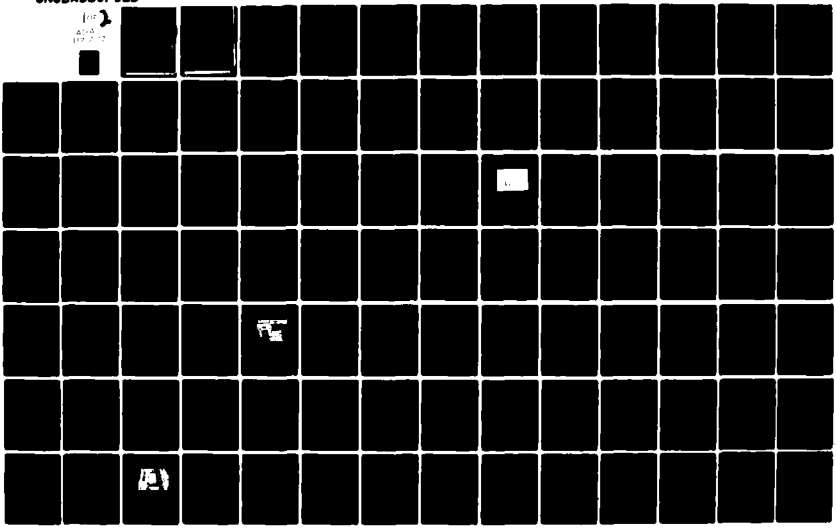

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A review was undertaken of the use of conventional geophysical methods for the detection of groundwater. Geophysical methodology has been used for a number of years in groundwater exploration. However, the total cost of groundwater exploration efforts has been minimal and, hence, there has been no extensive development of specific techniques and procedures for exploring for groundwater.

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20. It is proposed that using currently available geophysical methods, namely electrical and seismic methods, in an integrated fashion (e.g. in a manner in which one measures multiple parameters) is the most viable way to undertake groundwater exploration. Instrumentation on the market today is applicable to groundwater exploration, and there does not appear to be the need for significant development of instrumentation. However, there is the opportunity to develop other more efficient methodologies, and also to develop both improved and enhanced interpretation procedures. These improved interpretation methods will undoubtedly rely quite extensively on microprocessor based hardware. Computerbased analysis of data improves the ability to interpret noisy data, and also facilitates the interpretation of data by inexperienced individuals. The computer hardware for implementing many proposed interpretation algorithms is now available.

As an additional part of this study, a very limited field experiment was undertaken in which three geophysical methods were used in an attempt to evaluate groundwater resources in the arid San Luis Valley of Southern Colorado. The three methods used were seismic refraction, self-potential, and DC resistivity. The field experiments with all three methods clearly pointed out their relative strengths and weaknesses. It is clear from the literature and the field work that a trained, experienced field crew should have good success in detecting groundwater with conventional geophysical methods. The problem is whether a relatively inexperienced group can use geophysical methods successfully with only minimal training.

FINAL REPORT

GEOPHYSICAL DETECTION OF GROUNDWATER

by

James K. Applegate, Richard D. Markiewicz,
and Brian D. Rodriguez
Exploration Research Laboratory
Colorado School of Mines

Submitted to:

Department of the Army
US Army Mobility Equipment Research &
Development Command
Fort Belvoir, Virginia

April, 1982

Geophysical Detection of Groundwater

Executive Summary

A review was undertaken of the use of conventional geophysical methods for the detection of groundwater. Geophysical methodology has been used for a number of years in groundwater exploration. However, the total cost of groundwater exploration efforts has been minimal and, hence, there has been no extensive development of specific techniques and procedures for exploring for groundwater. The purpose of this report is to summarize the applicability of currently available geophysical methods for detecting groundwater and the relative success one might expect.

It is proposed that using currently available geophysical methods, namely electrical and seismic methods, in an integrated fashion (e.g. in a manner in which one measures multiple parameters) is the most viable way to undertake groundwater exploration. Instrumentation on the market today is applicable to groundwater exploration, and there does not appear to be the need for significant development of instrumentation. However, there is the opportunity to develop other more efficient methodologies and also to develop both improved and enhanced interpretation procedures. These improved interpretation methods will undoubtedly rely quite extensively on microprocessor based hardware. Computer-based analysis of data improves the ability to interpret noisy data, and also facilitates the interpretation of data by inexperienced individuals. The computer hardware for implementing many proposed interpretation algorithms is now available.

Other geophysical schemes may also lend themselves to groundwater exploration and may actually provide better results than have been obtained. The potential for enhanced groundwater exploration may lie with methodologies such as time-domain electromagnetic methods to improve the measurement of resistivity, and the use of shallow seismic reflection. These methodologies need to be evaluated and perhaps incorporated in future exploration schemes. The development of appropriate semi-automated interpretation methods is critical to the implementation of the afore discussed methods and also to newly developed methods.

As an additional part of this study, a very limited field experiment was undertaken in which three geophysical methods were used in an attempt to evaluate groundwater resources in the arid San Luis Valley of southern Colorado. The three methods used were seismic refraction, self-potential, and DC resistivity. The field experiments with all three methods clearly pointed out their relative strengths and weaknesses. It is clear from the literature and the field work that a trained, experienced field crew should have good success in detecting groundwater with conventional geophysical methods. The problem is whether a relatively inexperienced group can use geophysical methods successfully with only minimal training.

Table of Contents

List of Tables

List of Illustrations

Geophysical Detection of Groundwater

Background

The detection of groundwater by geophysical methods has been of interest for a number of years in areas of the United States where water is difficult and expensive to find. Groundwater is also of interest in many other parts of the world. It is a commodity that will become even more difficult to find and of more value as surface water sources become contaminated or depleted.

Conceptually, the location of groundwater by geophysical methods should be straight forward. The presence of groundwater in a rock significantly changes both its electrical and seismic properties. However, the change of physical properties when the rock is buried in the subsurface proves to be non-unique. In other words, changes in other rock properties, e.g. rock type, (the dry rock) may give the same geophysical anomaly as going from one rock type (the dry rock) to the saturated rock. Hence, there is ambiguity in the interpretation of the existence of groundwater in the subsurface. In addition, there are geological conditions that may cause groundwater to be difficult to produce even if it is present and detected.

Like other mineral commodities searched for by geophysical methods, it is necessary to improve resolution when exploring for deeper and deeper resources. A shallow resource, within about 50 ft of the surface, is relatively easy to find. When the resource is buried at a depth of several hundred ft, it becomes more difficult to find and, when it is more than 1,000 ft deep, it becomes much more difficult to find. Hence, the resolving power of various geophysical instrumentation and its response to the presence of groundwater in the subsurface, must be considered along with the various geological conditions and the constraints these geological conditions will impose on the application of geophysics.

The purpose of this report is to evaluate current state-of-the-art methodology in groundwater detection, by reviewing literature describing past exploration efforts, analyzing this information in light of the geology in areas of particular interest to MERADCOM, and to conduct limited field experiments. The report will include an analysis and recommendations on the application of various interpretation techniques for detecting groundwater.

Geophysical Methodology

Geophysical methods are numerous. However, for the purposes of groundwater detection, it appears that to search directly for groundwater, there are only a few applicable geophysical techniques which measure the physical properties of rocks that will be changed by the presence of groundwater. The remaining geophysical techniques may be useful only for defining structural controls which could provide a trap for groundwater.

Gravity and magnetic measurements appear to be of limited use for groundwater detection. These potential field methods respond to substantial changes in bulk density, and magnetic susceptibility, respectively. Neither of these properties are related to small-scale aquifer characteristics. These methods appear to be useful only in defining structure which may allow the entrapment of water. Hence, it is not anticipated that, in a standard application of geophysical methods in the field, gravity and magnetics will be widely applied.

Radiometric methods have some use for assessing the presence of groundwater in the subsurface. However, this use is principally in borehole surveys. There is no apparent useful application of radiometric methods in surface exploration for groundwater and, hence, they will be dismissed in this study.

The principal exploration methods for groundwater appear to be electrical and seismic methods. These are most applicable because water significantly alters the measured physical properties. Thus, this study concentrates on applications of conventional seismic and electrical exploration methodology.

Constant thought, however, was also given to deriving a method that would be both innovative and would directly detect groundwater. Currently, there is no "black box" that uses geophysical measurements to detect groundwater directly. However, it is conceivable that, with the right combination of geophysical measurements and the right integration of the data for a comprehensive interpretation, a technique could be derived which would provide a great deal of confidence in the ability to find groundwater. To develop methodology like this takes extensive work and long development time. Hence, for this study, efforts were concentrated on using readily available instrumentation and technology so as to optimize the ability to find groundwater within time and budget constraints.

An important additional constraint is the use of equipment that is field reliable, portable and easy to operate. It was first postulated that this equipment would be in the form of instrumentation that could be operated by a soldier with little or no training. A group of these soldiers would take the instrumentation to the field, make measurements and then, using some interpretation scheme such as nomograms, graphs, etc., derive the depth to groundwater without the aid of any professionals.

With the evolution of instrumentation and the optimization of microcomputing, it does not appear to be a significant problem in miniaturization of equipment for field portability. A major constraint, however, does appear to be the reliability of the equipment and the ease of subsequent interpretation. It is, of course, not useful to have very sophisticated equipment that is marginally useful; rather the equipment must be reliable in the field and easy to repair when it does break down. Also, data processing and interpretation must proceed in as easy a fashion as possible so that the data interpretation can be optimized. It is not useful to acquire data over a significant period of time and then have to spend months interpreting it. Therefore, to adequately test and use geophysical methods, it is necessary to develop some expertise with them and to carry out studies in areas of known groundwater occurences to evaluate the ease of data acquisition and interpretation.

The three methods principally discussed in this review are two electrical methods (self-potential and electrical resistivity) and seismic refraction. The application of other geophysical methods is, of course, possible and could provide useful data but they will require further work. Some methods that may fit in very well with this effort are the electromagnetic methods which are often a quicker and easier way to measure electrical properties of rocks than conventional DC resistivity methods. In addition, high-resolution seismic reflection methodology may be useful to evaluate subsurface water. However, this methodology is more difficult to apply and more laborious in the analysis of the data. Other technology which may be useful in the direct detection of groundwater is the combined use of shear and compressional waves. However, some of these methodologies clearly dictate the need for specially trained groups of water detecting technicians rather than a group of marginally trained personnel.

The three methods on which the study concentrates are relatively simple in theory and have been applied for many years in engineering, mining, and groundwater applications. However, the analysis and interpretation of geophysical data in groundwater exploration is often difficult. Hence, a brief review will be made of the theory behind each operation. In addition, more detailed descriptions of the application of seismic refraction, resistivity and self-potential methods are included in appendices. Note the theory presented here is not detailed. Concentration is on the application of these methods to groundwater exploration. Field procedures are also described which indicate how groundwater exploration methodology may be applied. In the appendices are outlines for manuals which would have to be prepared if relatively untrained individuals were to use these techniques.

Summarized in Table 1 are the general characteristics of geophysical methods considered. This table was derived in discussions with Dr. Ron Reese of the Defense Science Board.

Principles of Applicable Geophysical Methods

Seismic Refraction

Seismic refraction is an exploration method that has been used extensively for years. There is no need for a detailed description of the theory which is presented in many elementary textbooks. However, one must keep in mind the target. Seismic refraction methods have been used for both large scale crustal studies and for shallow engineering studies. The engineering and groundwater studies generally concentrate on mapping shallow interfaces. Often times this interface is the sediment rock interface. This, of course, may not be significant in groundwater exploration. What may be significant in groundwater exploration is determining the contact between the dry, near-surface materials and the saturated, near-surface material. To do this, one must look at not only the depth to various interfaces, but also the velocity of the materials. The velocity is the only real diagnostic tool for directly assessing groundwater with refraction methods. Unfortunately, this diagnostic tool is not always indicative of only groundwater. It may also be representative of changes in rock type. Thus, while mapping the possible location of groundwater is feasible using the seismic refraction method, the certainty that it is groundwater and not a

TABLE 1

GROUND WATER DETECTION

MATRIX

	D.C. RESISTIVITY	E. M.	SP	SEISMIC REFRACTION	SEISMIC REFLECTION	RADAR
1. Depth Limitations - General Application	more than adequate 10,000 ft	1,500 ft	200 ft	more than adequate 10,000 ft	10,000 ft	10-200 ft
2. Depth Limitations - Current Specialized Application	logistics 2,000 ft	1,500 ft	100 ft	500 ft	2,000 ft	100 ft
3. Depth Limitations - Optimum for groundwater detection	2,000 ft	500 ft	200 ft	1,000 ft	2,000 ft	150-200 ft
4. Depth Limitations - Maximum Capability	10,000 ft	4,000 ft	300 ft	10,000 ft	10,000 ft	150-200 ft
5. Ability to Discriminate Groundwater - Thickness of aquifer as percent of burial depth	15%	20%	10%	10%	5%	5%
6. Thickness of Aquifer	10-250 ft	10-300 ft	10-200 ft	5-300 ft	10-300 ft	5-300 ft
7. Types of Groundwater	All except very fresh in clean sand		Fresh	All	All	Fresh
8. Fresh Water Versus Bound Water	No	No	No	No	No	No
9. Skill/Training Required for Interpretation*	2 mos-class 2 mos-field	2 mos-class 4 mos-field	1 mo -class 4 mos-field	2 mos-class 4 mos-field	6 mos-class 4 mos-field	1 mo -class 2 mos-field

*Groundwater Geology
*Electronics
*Field Methodology
*Theory

TABLE I (cont.)

GROUND WATER DETECTION

MATRIX (PAGE 2)

	D.C. RESISTIVITY	E. M.	SP	SEISMIC REFRACTION	SEISMIC REFLECTION	RADAR
10. Speed of Data Evaluation expressed as percent of field time						
a. current	100%	100%	100%	100%	200%	25-400%
b. projected	50%	50%	50%	25%	75%	50%
11. Transportability of Equipment	Very good	Very good	Excellent	Very good	Good	Excellent
12. Ruggedness of Equipment	Good	Good	Good	Good	Fair-Good	Good
13. Speed of Coverage** (Miles/Day)	1	1.5	10	1	1	10-15
14. Equipment Availability	Off the Shelf	Off the Shelf	Off the Shelf	Off the Shelf	Off the Shelf	Off the Shelf
15. Operational Capability of Current Instrumentation**	1,000 ft Good	1,500 ft Good	200 ft Excellent	500 ft Good	2,000 ft Good	150-200 ft Good
16. How much instrument improvement with development	2X	2X?	2X? better theory	5X	5X	3X
17. Probability of detecting ground water within the optimum depth range	60%	50%	50%	40%	40%	60%

** Well designed field equipment for this work could significantly improve speed of coverage.

change in rock type is less than desirable. This, again, supports the need for integrated exploration.

DC Resistivity

DC resistivity methods have been widely used to determine lateral and vertical changes in earth resistivity. Through a number of different expressions such as Archie's Law, the relationship of the resistivity of a formation to its porosity and water saturation can be determined. This is like the seismic refraction method--a reliable indicator of groundwater--if one can be certain that there are no changes in rock properties, e.g. porosity, rock type, etc. The method of resistivity sounding commonly employed is the Schlumberger array. This appears to be the most applicable technique in defining the depth to water and the resistivity profile with depth. As with the refraction method, there is much literature on the theory and practice of DC resistivity soundings. This is covered more fully in the DC resistivity appendix.

Self-Potential

The spontaneous potential (self-potential, SP) method has been widely used in mineral exploration. It is also widely used in logging applications in petroleum exploration. The basic principal is that changes in permeability, water saturation and ion content of the fluids causes an ionic effect which creates a natural potential within the earth. This can be caused by sands and shales in a hydrocarbon environment and sulfide mineralization in a mining environment. It has been widely used in geothermal exploration in the location of the higher fluid ion content in the geothermal environment. The self-potential method is not as quantitative in terms of structural information as resistivity and seismic measurements, but it may be a more direct indicator, because it is sensitive not only to presence of groundwater, but also to the flow regime. The SP survey can easily be carried out in conjunction with a resistivity survey using similar equipment and utilizing similar field efforts. Thus the next logical step--is to use multiple geophysical methods to determine the details of the geological structure. Extremely useful results may be obtained, by using multiple geophysical methods to more confidently predict the presence of groundwater.

Of course, this emphasizes the fact that a knowledge of the geology and its effects on various geophysical methods is extremely important in assessing the application of various methodologies to a problem. It is important that the person in the field realize that certain geological conditions affect the measurements and, only then is the person more able to fully evaluate the problem.

Findings

To better analyze the individual effectiveness of the various geophysical methods suggested for groundwater exploration, and to use the various geophysical methods in an integrated manner, a groundwater exploration program was undertaken in the semi-arid San Luis Valley of southern Colorado.

This area is very dry, with alluvial fans extending from the Sangre De Cristo Mountains into the valley. The presence of thick alluvial sequences derived from near-by mountains overlying bedrock is somewhat analogous to the problem that MERADCOM proposes to solve.

In this area, resistivity, SP and refraction studies were undertaken. The results are presented in the appendices describing in more detail the various exploration methodologies, including a summary of the findings. The results clearly suggest that the methods are not a panacea. No one method yields perfect results; no one method yields unambiguous results. It is possible from the different data sets to surmise whether there might be groundwater, and the exploration study supports the point that the use of an integrated exploration program is important. It appears from this exploration program that the SP method detects the presence of fresh groundwater (Figure 1). This was in the vicinity of a seasonal stream that was still carrying water. From the presence of a well within 100 ft (20 m) of the stream, we know that a depression cone existed underneath the stream, i.e. the leakage of water into alluvium is very rapid and, hence, the water is at significant depth very quickly. However, the SP method clearly defined some structural effects of the groundwater. Whether one can separate these effects from the background noise and from the depth effects or from mineralization is questionable. It does appear, however, to be a method worthy of

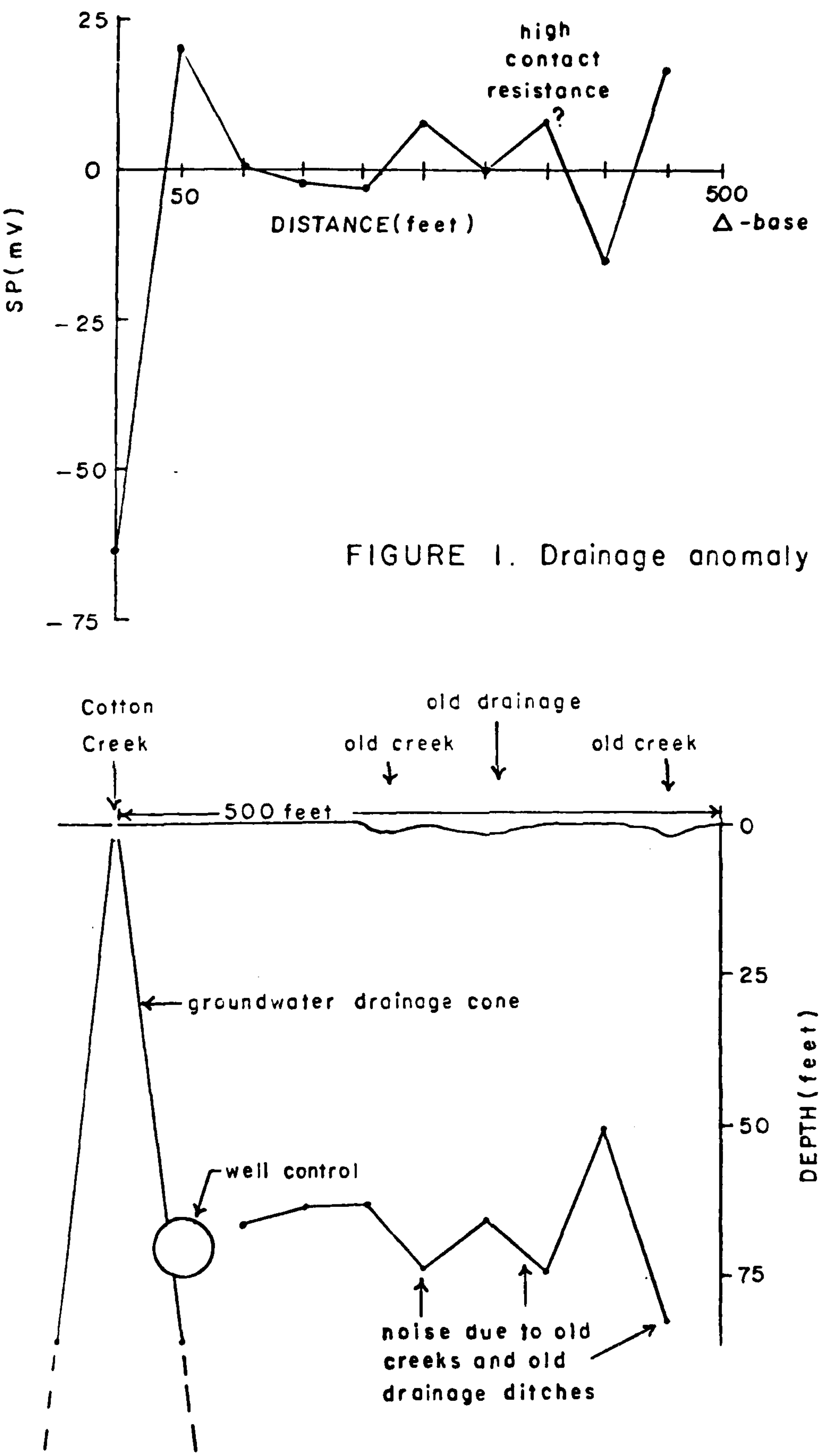


FIGURE 1. Drainage anomaly

further study. Resistivity soundings run in this vicinity and also further out from the mountain front indicated a near-surface semi-conductive zone which is probably representative of the near-surface moisture, a more resistive zone and a more conductive deeper zone. With the resistivity method alone, it is not possible to confirm what the more conductive deeper zone is. In fact, this more conductive deeper zone may be a water saturated sand or it may be a clay lens with bound water and a high ion content. This is difficult to discern. However, the apparent infiltration observed from the SP data may indicate a recharging of an aquifer. A refraction profile was also run throughout much of the area, which allowed the determination of the depth and the velocity of the substructure. From these velocities, it may be possible to discern whether water is present or not. Again, however, this is not a truly definitive tool, e.g. the velocity of water is approximately 5000 ft/sec (1500 m/sec), hence, if the velocity of the rock unit is below 5000 ft/sec (1500 m/sec), it indicates that the rock is not saturated with fluid. There may be water in the pore spaces, but it is not at a condition of total saturation. However, if the velocity of the rock is above 5000 ft/sec (1500 m/sec), there may be water in the pore spaces. It is also possible to have rocks with extremely limited fluid content that have a velocity above 5000 ft/sec (1500 m/sec) due to the nature of the structure of the rock. In other words, the rock may have inherent strength that indicates a high velocity without the presence of water.

This implies that dual measurements be made as a minimum effort in the field. The use of the refraction method and the resistivity method together would allow a better definition of the physical properties of the rocks at depth and allow a higher confidence level for assessing the presence or absence of groundwater. The SP method, the resistivity method, and the refraction method may be very useful together. If it can be illustrated that, in a number of different conditions the SP method responds to the interface between saturated and non-saturated rock, then one can detect the presence of water and, consequently, use either the refraction method or the resistivity method to determine the depth to this interface.

Unless a "black box" is developed in the near future, the best hope for locating groundwater is the integrated exploration approach.

Conclusions

The effort at the Colorado School of Mines in the past year has concentrated on assessing the applicability of current geophysical technology in groundwater exploration. While this effort has received much study over the past few years and while geophysical methods have been applied in groundwater exploration for many years, there is no definitive exploration tool for the detection of groundwater.

The geophysical techniques with the greatest immediate potential for success in military groundwater exploration efforts are DC resistivity, seismic refraction, and SP. Table 2 summarizes the advantages and disadvantages of these methods. None of these methods used alone has a 100% success rate. However, when used in an integrated manner, the success rate improves substantially.

This is not meant to preclude the use of other methods such as electromagnetic (which measures conductivity, the reciprocal of resistivity), and shallow seismic reflection, which if further developed may result in groundwater detection capabilities greater than currently available.

Specifically, we conclude:

1. Further refinement and development of current methodology is appropriate. It does not appear possible to significantly improve seismic refraction and DC resistivity techniques by anything less than an elaborate research program. However, there may be minor refinements in interpretation and analysis that would be useful to pursue, including the development of automated interpretation and modelling schemes on microcomputers. It is probable that more improvement could develop from further research into the SP method.

2. The development of new methods for groundwater exploration may be fruitful. This may include the development of an exotic groundwater exploration method from modifications of more conventional approaches. For example, one may determine that the combination of shear wave and compressional wave reflection and

Table 2 - Advantages and disadvantages of principal geophysical methods

SEISMIC REFRACTION METHOD

Advantages:

- The equipment already exists to run seismic refraction lines and record the data produced.
- Seismic refraction lines may be set up and run by two people with one four-wheel drive vehicle.
- The refraction technique has been in use since the 1920's; therefore, a large body of literature exists concerning interpretation of refraction data.
- No excavations, other than a shallow hole for the explosive source, are necessary to run the surveys.
- About 3-10 seismic lines can be run in a 10-hour field day, not including adverse travel conditions.
- The interpretation of the data requires a hand calculator, but no other more sophisticated equipment.

Disadvantages:

- The accurate interpretation of seismic refraction data depends upon having a certain amount of technical expertise, and adequate experience.
- By the nature of the method, exploration to a depth of 1,500 ft would require: running a seismic line 4,500 to 7,500 ft long; a rather sizable explosive source of seismic energy; burial of the charge perhaps 10 feet deep; several shots to provide adequate coverage.
- Explosives must be available to the exploration party.
- A saturated zone cannot be detected in every case because the accoustic properties of the saturated zone may not be unique, or sufficiently different from the surrounding rocks.
- Running refraction lines over frozen ground results in often difficult interpretation problems.

Table 2 (continued)

D.C. RESISTIVITY METHOD

Advantages:

- The equipment already exists to run D.C. resistivity surveys.
- D.C. resistivity lines may be set up and run by three people with one four-wheel drive vehicle.
- The technique has been in use for many years, therefore, a large body of literature exists concerning interpretation.
- No excavations are necessary to run the surveys.
- About 3-10 D.C. soundings to depths of 500 ft can be run in a 10-hour field day, not including adverse travel conditions.
- Simple interpretation of the data requires a hand calculator and matching curves, but no other more sophisticated equipment.

Disadvantages:

- The accurate interpretation of D.C. resistivity data depends upon having a certain amount of technical expertise and adequate experience.
- By the nature of the method, exploration to a depth of 1,500 ft would require: end-to-end profiles of 4,000 to 5,000 ft; a large battery source and/or a portable generator source; and sensitive receiving gear.
- Sounding to depths greater than approximately 750 ft creates logistical problems of handling long lengths of wire, and more care for data acquisition which significantly slows down the survey.
- A saturated zone cannot be detected in every case because the electrical properties of the saturated zone may not be unique, or sufficiently different from the surrounding rocks; or because the zone is of inadequate thickness.
- D.C. resistivity is not useful for detecting conductive zones beneath highly conductive zones.
- Highly resistive, near-surface material requires extra effort to get current into the ground.

Table 2 (continued)

SELF-POTENTIAL METHOD

Advantages:

- The equipment is rugged and reliable for field use.
- All the equipment is relatively inexpensive (about $500) and is available off-the-shelf.
- The self-potential survey is extremely mobile; all equipment can be carried easily by one person, and the entire survey can be performed alone.
- No excavations, other than a shallow hole (4 to 8 in) for the electrode, are necessary to perform the survey.
- About 2 line miles/person can be run in a 10-hour field day, including adverse travel conditions.
- Very minimal training is required to perform the survey competently.
- The interpretation of the data may require a hand calculator, though no other more sophisticated equipment. All results can be interpreted in the field.

Disadvantages:

- A saturated zone cannot be detected in every case because the method is sensitive to fresh and ultra-fresh groundwaters only.
- Performing self-potential lines over frozen ground results in often difficult interpretation problems.
- The self-potential method has been in use since 1830, how ever, a large body of literature does not exist concerning the interpretation of self-potential data.
- The accurate interpretation of self-potential data depends upon having a certain amount of technical expertise, and adequate experience.
- Maximum groundwater depth detection is about 300 ft.

refraction studies would produce a definitive analysis of groundwater presence or absence. Utilization of sophisticated electromagnetic sounding technology may also be very successful.

3. The use of existing methods in combination to improve one's confidence in groundwater exploration is a very significant improvement. This would involve the acquisition and inversion of multiple data sets using sophisticated data gathering and data reduction capabilities. The art in microprocessor development is such that on-site data gathering and reduction is possible. It remains for task specific hardware and software to be developed for groundwater exploration. Unless a "black box" is developed in the near future, the best hope for locating groundwater is an integrated exploration approach.

As the exploration plan is currently formulated, it is clear that a high confidence level from single and multiple geophysical methods will require the use of fully trained individuals. Therefore, if the US Army is to implement groundwater exploration programs, they must train a group that will perform these services. This group should include personnel with some technical background. But with an appropriate training program conducted either within the Army or at some other training facility, a level of expertise could be established that should be adequate to operate under most circumstances. As a team works together, their skills and confidence would improve and thus, their success rate would also improve.

This trained team approach offers the best surface exploration program available today if they are trained to use multiple geophysical methods. The success rate would be much less if the team were trained in only one method and might be very poor in certain geologic environments. However, with an understanding of groundwater geology, with practical experience and with the evolution of technology, a competent exploration team could provide the Army with a high success rate in defining groundwater under relatively adverse conditions. This competent exploration team would be far more successful than simply drilling for groundwater, both logistically (mobility) and statistically.

Appendix A - Guide for the Use of the Self Potential Method for the Detection of Groundwater

I. Theory of the method

A. Streaming potential

1. Electrokinetic coupling

When water is forced to flow through a porous medium, such as a rock, a voltage potential may be generated. In the earth, streaming potentials may be generated by the flow of fluids along aquifers (Figure 1), faults, geologic contacts, and also possibly by the circulation of geothermal fluids (Corwin, 1978).

2. Case histories

Ogilvy, et al (1969) have observed negative anomalies as great as 50 millivolts (mV) over areas where water was leaking through fissures in the rock floor of a reservoir. Bogoslovsky and Ogilvy (1973) observed a positive anomaly of 55 mV amplitude that mirrored a groundwater depression cone that surrounded a well pumping from a depth of 50 ft (16 m).

B. Sources of noise

1. Thermoelectric coupling

When a temperature gradient is maintained across a sample of rock, such as in the case of a geothermal system or a coal burn, a voltage gradient will be generated across the sample. A survey performed at Marshall, Colorado showed a strong well-defined anomaly of 140 mV peak amplitude directly over the burning zone of a coal mine fire which was at a depth of 30 ft (10 m) (Corwin and Hoover, 1979).

2. Telluric currents
   Temporal variations in the Earth's magnetic field generating long-period telluric currents may reach several hundred mV/mi over resistive terrain (Keller and Frischknecht, 1966).

3. Conductive mineral deposits
   Negative self-potential anomalies usually less than or equal to a few hundred mV are seen over the top of conductive mineral deposits (Corwin, 1978).

4. Cultural activity
   Populated areas and even unpopulated areas may have stray currents from cultural activity reaching amplitudes of tens or hundreds of mV/mi at distances greater than 3 mi (5 km) from the source (Hoogervorst, 1975). Sources include power lines, electrical grounds, corrosion of pipelines or metallic junk, pipeline corrosion protection systems, well casings, plowed fields, cultivation, irrigation, agricultural chemicals, as well as any other activities in the area of an electrical nature. The stray currents may take almost any form (Figure 2) from individual spikes or pulses and series of sinusoidal or square waves to irregular variations or even steady amplitudes (Corwin and Hoover, 1979).

5. Resistivity variations
   Resistivity changes across faults or geologic contacts often give short-wavelength signals of several tens of mV, which can mask a streaming potential generated by the flow of groundwater near the fault or contact (Corwin and Hoover, 1979). As the self-potential (SP) survey crosses a geologic contact or fault, an asymmetric anomaly is generated whose absolute value is smaller on the more conductive side of

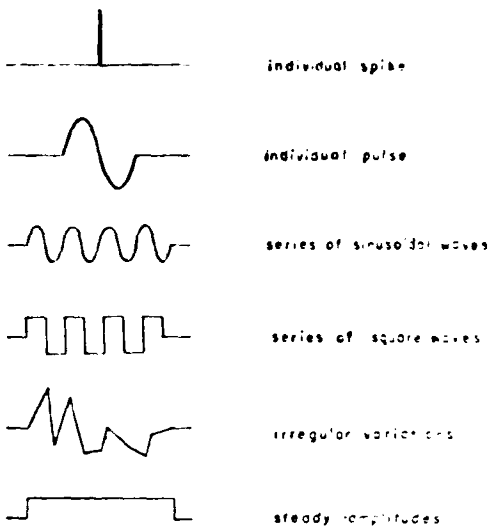


FIGURE 2. Forms of stray currents

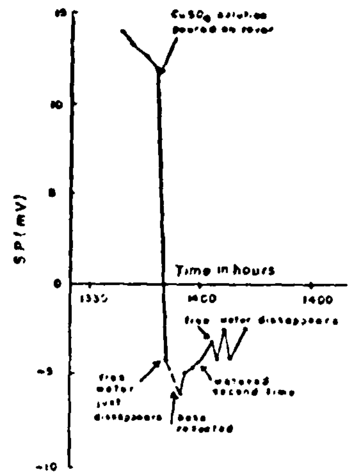


FIGURE 3.
Variations in watering the electrodes

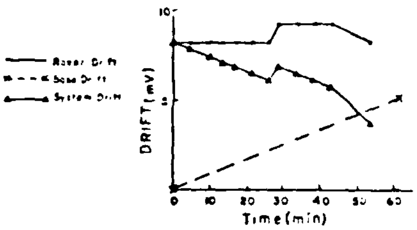


FIGURE 4. Drift

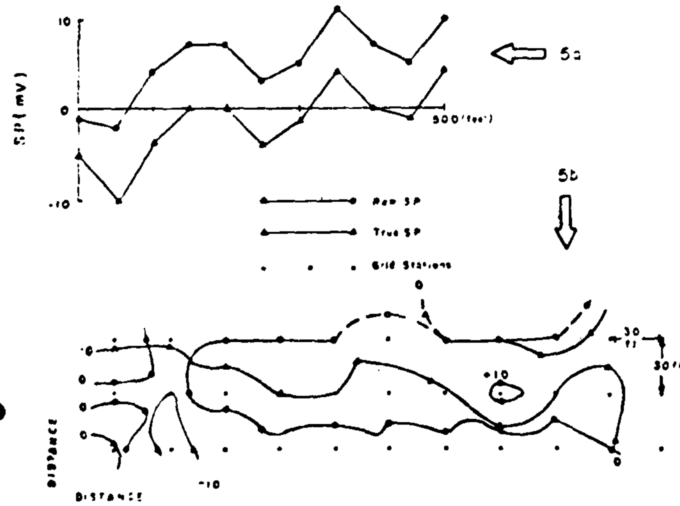


FIGURE 5a & 5b. Polarization error

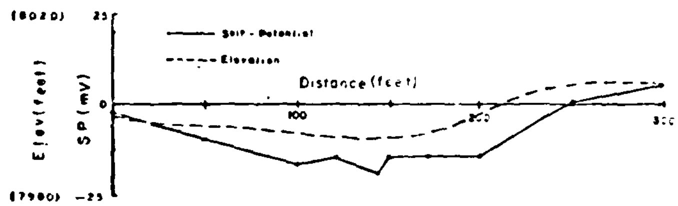


FIGURE 6. Topographic effects

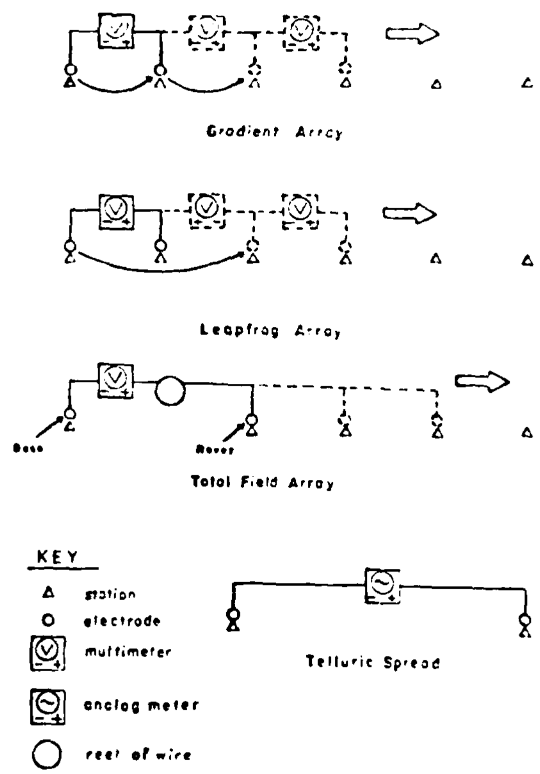


FIGURE 7. Arrays

the contact as compared to the absolute value on the more resistive side (Fitterman, 1979).

6. Electrochemical effects
Variations in electrode-to-ground contact account for much of the background noise in point-to-point observations due to variations in soil chemistry, temperature, and moisture content. Amplitudes may reach plus or minus 10 mV, and have wavelengths as short as a few cm (1 in) (Corwin and Hoover, 1979).

7. Electrochemical concentration cells
Chemical concentration cells such as pegmatite veins and silicified zones may contribute anomalies as large as tens of mV (Corwin and Hoover, 1979), and the weathering of alunite has been attributed to anomalies as large as -1800 mV (Gay, 1967) and -700 mV (Kruger and Lacy, 1949).

8. Soil moisture
Variations in soil moisture cause variations in self-potential as large as a few tens of mV (Corwin and Hoover, 1979), because the electrode in the wetter soil will become more positive (Poldini, 1939). This includes swamps and stagnant water.

9. Watering the electrodes
While watering the electrodes during a resistivity survey does not cause adverse readings, watering the electrodes while take self-potential measurements may cause serious variations in the data, as much as tens of mV (Figure 3).

10. Drift
Drift is a major source of nonreproducibility in self-potential measurements. As the moisture, tem-

-erature, and chemical content of the electrodes adjust to the same parameters in the earth, what is called drift will be observed (Corwin and Hoover, 1979). This is a steady increase or decrease in voltage potential over a period of time (Figure 4). An increase will occur when the porous junction of a base station electrode dries. A decrease will occur if it absorbs ground-water ions over a period of time (Corwin and Hoover, 1979). Neglecting to correct for drift may result in tens of mV error (Figure 5).

11. Uneven topography
    The voltage potential may be affected by uneven topography (Figure 6) distorting current flow patterns (Grant and West, 1965). In areas of uneven topography, near-surface resistivity may also vary considerably from point-to-point, thus making it difficult to separate the topographic and resistivity effects (Corwin and Hoover, 1979).

12. Electrode polarization
    Electrode polarization is a spurious voltage potential created by the electrodes, due to contamination of the electrolyte of the electrode or variations in the porous junction moisture content or due to variations in the electrolyte temperature of the measuring electrode with respect to the reference electrode (Corwin and Hoover, 1979); 0.5 mV per degree Celsius (° C) for saturated copper-copper sulfate electrodes have been reported (Ewing, 1939; Poldini, 1939). Just less than 0.25 mV/° C have been reported for silver-silver chloride electrodes (Corwin and Conti, 1973). The more variations one enters into the SP survey, the less reliable are the values of SP measured. This is one reason why the total field array (Figure 7) is preferred over the gradient

leapfrog arrays (see section III: Field Procedure, subtitle C: Performing the SP survey, paragraph 2: Array configurations).

II. Instrumentation

A. Old

With the advancement of electronics in the last decade, the older equipment necessary for an SP survey has quickly become obsolete. Also, the cost of the equipment has been reduced significantly. With the repair of older equipment and replacement of parts becoming more and more difficult, it is not advisable to pursue the usage of such equipment. The usage of state-of-the-art equipment is more profitable, both economically and in the precision of data collected.

B. New

Equipment necessary for an SP survey include: A multimeter, electrodes, a reel of wire, a tape measure, and a tool box (Figure 8). Supplies necessary for an SP survey include: copper sulfate crystals, distilled water, a bottle, a backpack, and a field notebook. Many of the supplies and equipment can be kept in the backpack during the survey.

1. Multimeters

Any multimeter which will read to the nearest mV with high accuracy and has a 10 megaohm (MΩ) input resistance will work satisfactorily in an SP survey. It is recommended that an LCD (Liquid Crystal Display) multimeter be used as it is much easier to read the values on the meter during the day. A multimeter is necessary to measure both voltage potential and circuit resistance (explained in Section III). Keep

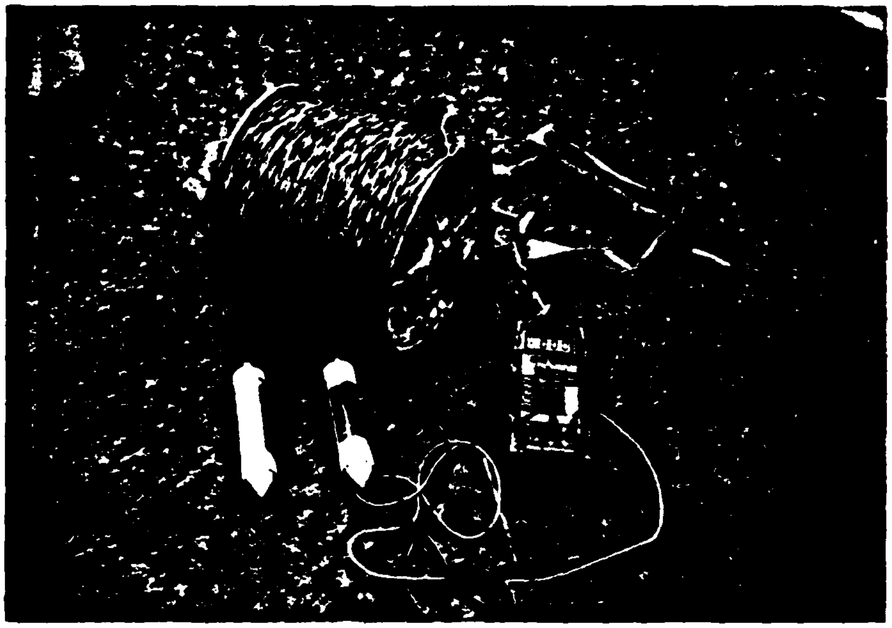


Figure 8. Groundwater exploration equipment: self-potential.

on hand an extra battery or two for the multimeter. Fluke manufactures several multimeters which are more than satisfactory. They are:

Fluke Model	Input Resistance	Price*
8020A	10 megaohm	$179
8022A	10 megaohm	$139
8024A	12 megaohm	$219
D800	10 megaohm	$125

* As of April 1981

2. Electrodes

Do not use copper stakes for the electrodes, as they will react chemically with the soil, producing spurious potentials. There are two types of electrodes one can use in an SP survey, both are nonpolarizing porous pots. One is the large size, longer life porous pots, usually around $70 per porous pot. The other is the smaller, less expensive, but more than satisfactory, Tinker & Rasor, $20 porous pot, available from Tinker & Rasor, P.O. Box 281, San Gabriel, California 91778, (213) 287-5259. Either of these is satisfactory. One will need three porous pots for the SP survey, but keep a couple extra in the backpack.

3. Reel of wire

Anywhere from 500 ft (150 m) of wire or more may be used for an SP survey. Anywhere from 16 to 22 gauge wire may be used as long as the total resistance of the wire is not exceedingly high, usually around 1 ohm. It is desirable to carry the wire on a reel with a handle to wind and unwind the wire during the course of the survey. For the heavier wire (lower gauge), it may be desirable to have a reel with shoulder harnesses so that it may be carried on the chest of the surveyor. For the lighter wire (higher gauge), a shoulder harness may be not be necessary; some cross piece on the reel is necessary though to allow the surveyor to hand-carry the reel. During the survey, keep one hand dragging on the spool at all times while moving between stations so that the spool never spins free creating a "rats" nest.

4. Tape measure
   A 300 ft (100 m) tape measure is usually satisfactory for locating all stations.

5. Tool box
   A tool box should include miscellaneous wire, alligator clips, wire strippers, a garden trowel and/or a rock hammer, flagging tape, electrical tape, a set of screwdrivers, and a stiff bristled (not steel) brush.

6. Bottle
   A plastic bottle can be used for the reference electrode bath (explained in section III). It is advised to keep the plastic bottle of copper sulfate bath out of the sun in the backpack during the survey.

7. Field notebook
   A field notebook is necessary for collecting the data. A "weatherproof" field book is appropriate, although a regular notebook may be used, as an SP survey is never performed in the rain (see section I, subtitle: B. Sources of noise, paragraph 8: Soil moisture).

C. Cost

Total cost of equipment for an SP survey can be as high as $1400 if the highest precision, newest equipment is purchased, which is more than satisfactory. Or when using economic discretion, the total cost can be as low as $500 for high precision, satisfactory, new equipment.

III. Field Procedure

A. Selection of survey lines

1. Topography

   Selection of areas with small or no variations in elevation is desirable. Simplicity in the interpretation of the SP data is directly proportional to the gentleness of the topography.

2. Geology

   Selection of areas with few lateral variations in substructure is desirable, as these selections will contribute towards simplicity in the interpretation of the SP data.

3. Potential noise sources

   Selection of areas where there is little or no cultural activity or scattered metallic junk or other possible noise sources (listed in section B: Initial survey, paragraph 5: Noting possible noise sources) is desirable, as this will improve the simplicity in the interpretation of the SP data.

B. Initial survey

1. Location of survey lines

   One should perform the SP survey in a grid pattern, which is made up of single lines in a parallel orientation. As with any survey, one needs to locate all measuring stations accurately on a map for proper interpretation and location of the self-potential anomalies.

2. Topography

   The data will be distorted in areas where there are large variations in topography. Note all these variations along and around the survey line. If possible, obtain a topographc map of the area. However, it is logistically better to choose a survey line that is in a flat area or area of constant, but gentle slope (which later may be recognized as a source of noise, Figure 6).

3. Geology

   If possible, obtain a geologic map of the area. This will help in interpreting the SP data acquired, even if all that is available is the general geology, e.g. knowledge of the geology may help in identifying the subsurface rock layer which serves as an aquifer for groundwater, also in identifying any possible mineral deposits in the area which may serve as possible noise sources to the SP survey.

4. Resistivity

   If possible, obtain a resistivity map of the area, either by previous surveys or performing a resistivity survey to obtain a map of resistivity for the area of concern.

5. Noting possible noise sources

When walking the survey line, either before or during the SP survey, take careful notes of and the location of the following:

a. old or new stream channels
b. old or new drainage channels
c. steam vents (geothermal activity)
d. surface ore deposits (mining areas)
e. power lines
f. electrical grounds
g. corrosive pipelines
h. metallic junk
i. irrigation
j. marshy areas or stagnant water
k. asphalt roads
l. variations in topography
m. variations in soil moisture
n. large variations in air temperature

C. Performing the SP survey

1. The electrical circuit

a. The measuring unit

The measuring unit includes the 10 MΩ multimeter, a reel of wire, and two porous pots.

b. The reference unit

The reference unit includes the 10 MΩ multimeter, one porous pot, and a plastic bottle containing a bath of saturated copper sulfate solution.

2. Array configurations

a. Gradient

Two measuring electrodes, separated at a fixed length are stepped along the survey line (Figure 7), and successive voltages are added to obtain the total field. However, when many such additions are done, small errors may accumulate to large values. Performing this survey in a closed loop is not always effective in determining the cumulative error, because polarization of an electrode pair may change in magnitude and polarity from one reading to the next (Corwin and Hoover, 1979).

b. Leapfrogging

Alternating the leading and following electrodes of a gradient survey (Figure 7) will help in reducing the cumulative error caused by electrode polarization (Corwin and Hoover, 1979).

c. Total field

This array by far, produces the most consistant readings of self-potential measurements. In a total field survey, a fixed base electrode, not to be moved for the duration of the survey, is used with a mobile measuring electrode (Rover, Figure 7). With the base electrode stationary throughout the SP survey, it serves as one less variant to the survey. Polarization errors will also affect the data gathered from this survey, but with the advantage that the error of each reading is limited to the maximum value of the polarization (Corwin and Hoover, 1979). Station spacing may vary from 5 to 50 ft (1.5 to 15 m) depending on the detail desired dictated by the variations in the SP distribution.

3. The measuring unit

a. Reel check

(1) Measure and record reel wire resistance. Contact one lead of the multimeter to one end of the wire and contact the other lead to the other end of the wire. Push the buttons on the multimeter so as to read the largest resistance scale. Infinite reading indicates an open (broken) wire which must be repaired.

(2) Measure resistance between either end of wire and frame of reel. This must read open (infinite) indicating no contact (short circuit) between the wire and the reel frame.

b. Seating the electrodes

Before seating any electrodes, the base electrode must be checked for polarization at the beginning of the survey. Also at the end of the survey, the very last measurement will be the polarization check on the base electrode. The procedure for checking polarization is explained in paragraph 4: The reference unit. After measuring polarization, tie-off one end of the reel wire to a stake or bush so the base electrode will not be pulled out of the ground. Attach that end of the wire to the base electrode terminal. Then seat the base electrode in the ground at the base station, usually the corner of the survey grid (or a previous hole, if tying into a previous line), and if possible, in a representative undisturbed soil site. Great care must be taken at each station to firmly insert the porous tips into small pits that penetrate the dry surface soil layer. These pits can be dug with a garden trowel or rock hammer, as the dry surface soil layer is usually no more than 4 to 8 in (10 to 20 cm) deep, even in desert soils (Corwin and Hoover, 1979). Clean any loose soil and rocks from the bottom of the hole. Then seat the base electrode in the hole by pushing down and rotating to ensure a good soil contact. Pile soil around the electrode to hold it upright and tamp the soil down thoroughly. Be sure no soil touches the electrode connector. Place a sun shade (rag) over the electrode and weight it down with rocks and/or soil. Contact resistance in the field is generally less than 30 KΩ requiring a 10 MΩ input impedance meter so as not to draw appreciable current from the electrode. Thus, if the porous pots are not seated properly in the ground, contact resistance will be higher, perhaps as high as 500 KΩ, requiring a multimeter with a 1000 MΩ input impedance. The rover electrode is seated in the same manner as the base electrode except that no tie-off of the other end of the wire is necessary, and the rover is to be seated at each station that is to be measured for its self-potential.

c. Noting the soil character

Take note of the soil type for each electrode site, as differing soil types may cause a spurious potential not related to groundwater. Also note any differences in soil moisture for the same reason, and if possible, note any temperature differences in the soil for every electrode site.

d. Electrode character

It is important to note any contamination of the electrolyte of the porous pot or any variations, if detectable, of the porous junction (porous tip) moisture content. And if possible, any variations in the temperature of the electrolyte should be noted. Also, if one is using a stationary base electrode in the survey, one should note any detectable drying of the base electrode's electrolyte, as this will cause drift in one's measurements.

e. Measurement of SP

Now that the porous pots are properly seated, the measuring circuit may be connected. Since one end of the wire is already connected to the electrode top of the base porous pot, connect the other end of the wire from the center of the reel to the black (negative) lead of the multimeter. Connect the red (positive) lead of the multimeter to the electrode top of the rover porous pot. With the functions on the multimeter set to read DC mV, the multimeter will read in mV the self-potential value to be recorded. It should take only a few seconds for the meter to settle down (a few minutes for some soils). This measurement should be made immediately, as the longer it takes to make a measurement, the more one polarizes the porous pots. The electrolyte leaking through the porous tip of the electrode will react chemically with the surrounding soil, if given enough time. So one should strive to make the measurement in the least amount of time.

f. Measurement of contact resistance

This measurement should be made immediately after the measurement of the SP. One simply changes the functions on the multimeter to read KΩ (for no more than two seconds). Return to the voltage function immediately, as the multimeter will drive current through the circuit, thus polarizing the electrodes. Record the value of resistance, rounded to the nearest KΩ. A reading of less than 200 KΩ indicates that the electrode ground contact was satisfactory. If the reading was greater than 200 KΩ, reseat the rover electrode or dig a new hole and repeat the measurements of SP and contact resistance. Immediately after a successful reading is recorded, time should be recorded and the circuit disconnected, either by turning the meter off or simply by disconnecting one of the wire connections. The latter is preferable as it saves on the wearing out of the on-off function on the meter. Remove the rover porous pot from the ground, brush any loose soil from the tip of the porous pot. If there is any chance that the station will be a future tie-in point (base station) between two SP surveys (e.g. extent of the survey exceeds the length of wire on the reel, thus requiring the base station to be moved), put flagging tape in the hole to mark it, and fill the hole with soil to keep the hole from drying out. Move on to the next station.

4. The reference unit

During the SP survey, once every half-hour and at the end of the day's survey, any polarization or drift on the rover electrode needs to be measured (the base electrode needs to be measured for its polarization/drift once at the beginning and once at the end of the survey). Assuming a total field survey is used (explained above), remove the electrode from the ground and clean the tip free of any soil with a stiff-bristled brush (not metallic). Then place the electrode into the bath of saturated copper sulfate solution. This solution should be made before the survey begins, and every effort should be made during the survey not to contaminate the solution with any soil or dust. The reference electrode will remain in the solution throughout the survey, as this is the reference from which one removes polarization and drift. The measurement is done by placing the dirt-free electrode into the bath of copper sulfate* solution and measuring the voltage potential in mV between the measuring and the reference electrodes. If possible, keep the bath at a constant temperature, as this will maintain the reference electrode at a relatively constant potential. Do not forget at the end of the day's survey to measure any polarization on the base electrode. This should be the last measurement of the day. A good format for the field notebook might be:

Station	SP (mV)	Polar (mV)	R (KΩ)	Time	Notes
0	- 3.8	0.6	5	1054	Base
1	-10.1	-	5	1057	met junk-10 ft
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
12	-44.3	2.3	10	1128	creek-3 ft

*be sure that the bath's electrolyte is the same as the porous pot's electrolyte.

5. Monitoring tellurics

Generally, tellurics are only a problem if the readings of SP begin to fluctuate. If high amplitude long-period tellurics exist for large scale SP surveys over resistive areas, then one must either monitor them or check with NOAA or another appropriate agency which monitors atmospheric conditions. One may be able to estimate the level of long-period telluric activity (see section I: Theory of the method, subtitle B: Sources of noise, paragraph 2: Telluric currents) by recording telluric variations with a separate analog meter across a stationary dipole (Figure 7) in the survey area. The telluric spread should be as long as and parallel to the largest SP survey line in the immediate area. Then one can estimate when the level of tellurics is interfering with the SP measurements. If it is desired to make quantitative corrections to the data, the apparent resistivity of the earth beneath the stationary dipole and the survey point must be known for a period equal to that of a recorded variation (Corwin and Hoover, 1979).

IV. Interpretation

A. Raw data

1. Plotting drift

Assuming the total field array was used to perform the SP survey, one simply plots drift vs time of both the base and rover electrodes for the entire survey. Since the polarization check on the base electrode was made only at the beginning and end of the survey, one only has two data points to plot versus time for the base electrode. Therefore, a straight line curve will fit the two data points. Since one measures polarization on the rover electrode after each half-hour, the rover will have many data points to fit straight line segments with. Both of these are illustrated in Figure 4.

2. Removing drift

Now we have a plot of the drift on each electrode. To remove the drift from the SP data, we must use the difference in drift, because when we measure SP with the multimeter, we are measuring the potential difference between the two electrodes, therefore to remove drift, we must use the potential difference in the drift. This is accomplished simply by subtracting the value of drift of the base electrode from the value of drift of the rover electrode, i.e. drift of the system = drift of the rover - drift of the base. Sometimes the drift of the system will be positive and sometimes negative, but whatever the value, it is to be subtracted from the SP data, i.e. true SP = raw SP - drift of the system. After removal of drift has been performed, one is ready to plot the true SP.

B. Adjusted data

1. Plotting SP

Assuming the total field array was used to perform the SP survey in a grid pattern, plotting distance vs distance and at each station the SP value in mV, will produce a contour map similar to Figure 5. Plotting SP vs distance for each parallel line of the grid allows a closer look at the detail in the SP measurements (Figure 1).

2. Noise

Certain noise sources (listed under section III. Field Procedure, subtitle B. Initial Survey, paragraph 5. Noting possible noise sources) will distort the self-potentials due to groundwater, as these noise sources themselves produce self-potentials in the earth. Zones of higher clay content in the earth will give rise to positive anomalies as there is an accumulation of positive ions. Accumulations of coarse detritus give rise to negative anomalies (Bogoslovsky and Ogilvy, 1973), and so these geologic conditions must be identified and carefully considered when interpreting SP data. Thus one must now note on each SP plot any noise sources that may exist. If any noise sources exist at stations which produced anomalies, one is forced to view those anomalies with skepticism as to their indicating groundwater.

3. Identifying groundwater

a. Anomaly sign

SP values near some groundwater structure may be either positive or negative, depending on whether the survey line crosses directly over an inflow (discharge) or an infiltration (leakage). Positive anomalies are characteristic of inflow water sites and negative anomalies are characteristic of infiltration sites (Bogoslovsky and Ogilvy, 1973).

b. Fresh groundwater

Streaming potentials are very sensitive to ultra-fresh and fresh ground waters. Brackish waters are very difficult to locate with the SP method. Thus, any SP anomalies, if associated with streaming potentials due to groundwater, are an indication of fresh groundwater.

c. Finding the zone of inflow

If a horizontally flowing groundwater channel is encountered in the field, a positive SP anomaly will be measured when the rover electrode crosses the zone of inflow. If the base electrode of the SP survey is stationed over a horizontally flowing groundwater channel, a negative SP anomaly will be measured as the rover electrode leaves the zone of inflow.

d. Contour of the water table

For water flow in a uniform permeable soil, the streaming potentials reflect the contours of the water table. The potentials (absolute value) increase in the direction of water flow and their intensity is proportional to the hydraulic gradients (Bogoslovsky and Ogilvy, 1973).

V. Self-Potential field results

A. Summary

Presently, the interpretation of self-potential measurements is not quantitative, but qualitative, detecting anomalous zones. The SP (self-potential) method should be used as a reconnaissance method to define the anomalous zones which may yield shallow, less than 300 ft (90 m) groundwater supplies, while other geophysical methods could be used to give more quantified results.

B. Results

1. The SP field experiment detected a groundwater structure down to a depth of investigation of just less than 100 ft (30 m). Figure 1 illustrates this groundwater structure.
2. The speed of coverage of the SP method will vary according to the sampling interval of the survey, however, a probable coverage rate might be three minutes per station. The field experiment yielded roughly five hours per line-mile for a 50 ft (15 m) sampling interval. Thus a one-man surveying team could cover two line-miles (3 Km) per day; a four-man surveying team (each with their own equipment) could cover eight line-miles (13 Km) per day, etc.
3. The resolution of the field study was about 10% with the SP indicating a depth to groundwater over a well at 80 ft (24 m) while the well yielded the groundwater level at a depth of 70 ft (21 m).
4. The SP survey proved to be extremely mobile; all equipment can be carried easily by one person, and the entire survey can be performed alone.
5. The SP survey proved to be sensitive to fresh groundwater.

6. The field experiment demonstrated the ruggedness and the reliability of the equipment. These factors along with its relative inexpensive cost and off-the-shelf availability makes the SP method a very attractive approach in the search for groundwater. It is also cheaper in the long run to purchase the equipment, as opposed to leasing it.
7. The operational capability proved to be 1,500 ft (450 m) in any direction and is easily handled by even one person.
8. No computer processing was necessary, and all results can be interpreted in the field. Approximately the same amount of time was needed to interpret the data as was needed to collect it.
9. With the training of personnel during the field experiment, the SP survey proved without variation to require very minimal training for the personnel to perform the survey competently.
10. Education required for competent interpretation skills would be:
    a. one month of lecture on SP theory, groundwater geology and electronics,
    b. two months of SP field experience.

Appendix B - Guide for the Use of the Seismic Refraction Method for the Detection of Groundwater

I. Principle of the refraction method

A. Critical angle

The seismic refraction method uses the seismic compression wave which has been critically refracted according to Snell's law. Snell's law is a mathematical description of the way in which light, sound and other wave phenomena propagate through media with different wave velocities. When the angle of approach (from the upper layer with a lower velocity to the lower layer with a higher velocity) is less than the critical angle, most of the wave energy passes through the interface into the underlying high velocity material. At the critical angle, however, the wave energy is "critically refracted", with most of the energy passing along the interface between the two layers. This is the so called head wave in refraction surveying. The head wave will continually emit energy back up into the low velocity material and thence to the surface. Detectors on the surface called geophones will pick up the energy from the head wave, which has travelled back up through the upper layer (overburden). This is the response which the operator looks for in conducting the refraction survey.

D. Interpretation schemes

Many methods exist for interpreting the seismic refraction data obtained in this manner. The method described herein is the so called reciprocal method (Hawkins, 1961; Barry, 1967). This method is more versatile than other methods which assume the beds to be planar and have limited dip angles. By using the reciprocal method, one can compute the depth to the layer of interest below each geophone station, enabling a much more detailed interpretation. In order that the reciprocal method be used on a given seismic line, the data should be gathered so that seismic wave arrivals come to a geophone station from both ends of the line. Interpreting the first line performed at a new site before continuing with other lines, allows modification of the program layout so that future shots will be in the proper locations to give more interpretable results.

II. Limitations of the method

A. Insufficient velocity contrast

One of the most important constraints on the method is dictated by the way in which waves are refracted in the earth. According to Snell's law, a difference in velocities, known as a velocity contrast, must exist between two adjacent layers in order for the wave to be refracted at the interface. If no such contrast exists, or if the contrast is very slight, the underlying bed may not be detected directly because the refraction at this interface was not great enough.

B. Blind zone

This condition is well known in seismic refraction prospecting (Soske, 1959; Domzalski, 1956; Hawkins and Maggs, 1961). With a certain combination of bed thicknesses and velocities, the first arrival at the surface from a given layer may be masked by arrivals from other layers both deeper and shallower. There exist certain subsurface configurations for which no arrangement of geophones can detect a given layer. Sophisticated methods exist for indirect detection of these blind zones, but they are rather time consuming for an effort such as rapid reconnaissance in search of groundwater.

C. Velocity inversion

A third situation which may exist is known as a velocity inversion. This is a rather fundamental constraint on the refraction method. It exists when an underlying bed below some overburden layer has a lower velocity instead of a greater velocity than the beds near the surface. The resulting refraction of the wave is deeper into the earth instead of shallower, thus no waves reach the surface from this low velocity layer. Therefore, it cannot be detected from the surface by this refraction method.

III. Instrumentation

A. State-of-the-art

The state-of-the-art in portable engineering seismographs has progressed rather quickly in the last five years, somewhat similar to the advances in handheld calculators and other portable electronic devices. Seismographs can be purchased which are light-weight and reliable under typical field conditions, without considerable research and development effort.

B. Enhancement seismographs

Seismographs for groundwater and engineering projects usually use a sledge hammer or explosive source. Those using explosives are considered in the next paragraph. For short spreads with distances between geophones of ten feet or so, a sledge hammer is an adequate energy source. In typical field operations, one person hits the hammer against a massive metal plate or sphere (a shotput works well in this regard). A triggering device on the hammer handle sends the zero time break to the seismograph at the moment of impact. By a process known as signal enhancement, waves from repeated blows of the sledge hammer are digitized and summed in the instrument memory. Random noise signals will statistically sum to zero when the number of blows is large. Conversely, true seismic signals will tend to add to large amplitudes after several blows, thus enabling the operator to "make the pick" of the arrival time of the seismic head wave. Instruments which operate by this method are termed "signal enhancement seismographs".

C. Single pulse seismographs

Seismographs which use an exposive source are commonly found where the distance between geophones exceeds ten feet. These instruments usually are capable of receiving and recording at least 12 channels of information simultaneously. The zero time break is internally generated by the instrument, as it sends the electrical pulse to detonate the blasting cap. Twelve or more geophones connected to the seismic cable receive signals through the earth from the explosion. The data is recorded digitally on magnetic tape, or on some kind of paper record as wave forms. Also a video screen is commonly available to display the data for quality assurance.

D. Representative products

An instrument such as the Geometrics Nimbus (trademark of EG&G Geometrics, Inc.) model ES-1210 seismograph is a good example of current capability (Geometrics, 1980). The instrument features signal enhancement on twelve channels with current data visible on a video screen. The memory may be frozen on selected channels while another shot or another hammer blow improves the signal on the rest of the channels. At the operator's option, filters may be used to elminate harmful noise. Finally, when satisfied with the appearance of the data, the operator sends the data to a magnetic recorder or prints it on paper.

IV. Field procedures

A. Equipment deployment

A typical field layout for hydrologic or engineering scaled refraction work would consist of a small, portable engineering seismograph, a seismic cable, with typically 10, 30, or 50-ft (3, 9, 15 m) geophone spacing, a geophone for each channel, and often one or two spare geophones per rig (Figure 9). The seismograph instrument has amplifiers, some means to record the data, and usually some sort of filter package. It is important to have enough battery power in the instrument, or more commonly, as external batteries (e.g. motorcycle batteries). Another important consideration is that seismic cables are often very fragile and need careful attention so as not to break the small wires inside the cable. Also, geophones are fragile inside the metal casing and do not stand up well to abuse such as stomping them into the ground.

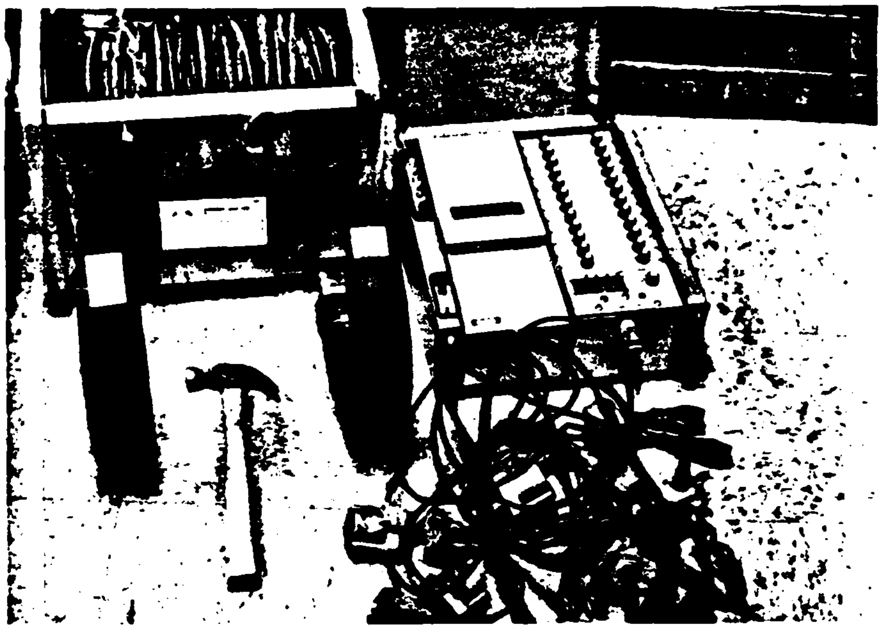


Figure 9. Groundwater exploration equipment: seismic refraction.

B. Areal considerations

In laying out seismic lines, it is often desirable to have some sort of surveying control over the landscape first. For continuous coverage, the crew may want to first put stakes or small "pinflags" along a surveyed line and then conduct the seismic survey. If some sort of surveying coordinate system exists, the interpretation of the data is made much easier. In conducting the first lines in a new area, the seismic crew may want to do on-the-end, center and off-the-end shots. If time is available to interpret the first few lines before proceeding with any further seismic lines, it becomes much easier to plan the next shots and get good overlap of data from both directions of shooting For subsequent lines, an overlap of one-half to one-third of a spread length, with shots on both ends may well be sufficient to map the refractor of interest.

C. Explosive sources

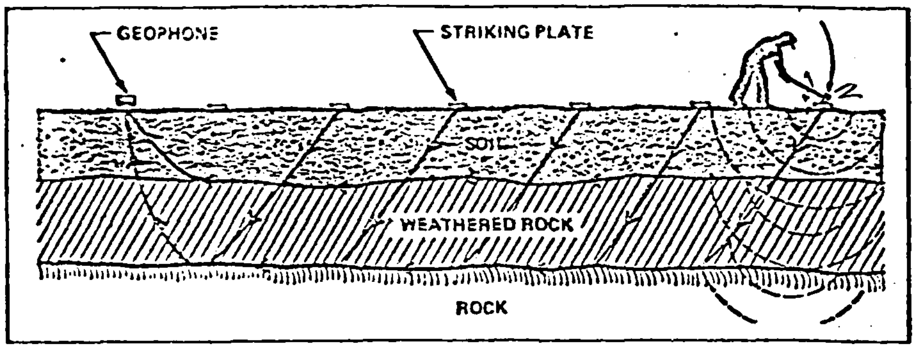
When using an explosive source, it is important to bury the charge if at all possible. This insures getting enough energy into the ground to achieve a strong event on the seismic records. A portable hand-held drill may be used to help bury the charge to an acceptable depth. A good shot depth is indicated by the charge not shooting much material into the air, while producing a dull sound rather than a sharp noise. The size of the charge needed is indicated by the first arrivals on the seismic records. If the first arrivals appear rounded in waveform rather than sharp, then more explosives should be used in the next shot. Some conditions, obviously, do not allow for good burial of the charge. These conditions would include a very gravelly desert surface where digging into the ground to bury the charge is difficult. In this case, a rather large surface charge should be used to insure that enough energy is transmitted into the ground to produce good wave arrivals.

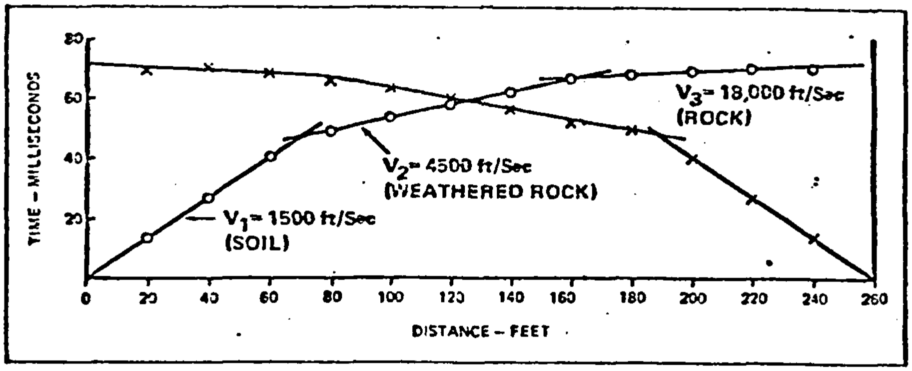
D. Hammer sources

When using a sledge hammer as a source, the operator at the instrument end of the line will be able to tell when enough seismic signal has accumulated in the instrument memory by looking at the waveform. If it is sharp enough to pick the first arrival, then no more hits with the hammer are needed. When the total length of the seismic line is greater than, say, 110 to 220 ft (33 to 66 m), 10 to 20 ft (3 to 6 m) geophone spacing, a hammer is a very inefficient source due to the large number of hits needed for each station. In this case, an explosive source should be used.

V. Seismic refraction field tests

Refraction studies were done along a test site on the east side of the San Luis Valley in south-central Colorado. The purpose of these studies was to determine if the saturated gravel layers that are believed to exist in the area could be detected using conventional engineering geophysical techniques. The tests were run with an SIE model RS-4 12-channel, seismograph system. The equipment consists of a compressional wave source (in this case, explosives), twelve geophones plus spares, an amplifier package included in the instrument, and a 12-channel recorder. A typical field layout for a similar, sledgehammer source is shown in Figure 10. Geophones were usually placed 50 ft (15 m) apart, although some of the lines were run with a 30-ft (9 m) geophone spacing for better definition of the subsurface. Shotpoints were located at the immediate ends of the seismic line, and up to 250 ft (75 m) off the ends of the line. Additional shots were sometimes used between channels 6 and 7 near the center of the lines to obtain better definition of the subsurface. At this site, survey lines were run along the





SEISMIC REFRACTION METHOD

FIGURE 10

road, the west boundary of the site. The lines were run essentially end-to-end so that a more or less continuous profile was obtained. A defect of this set-up was insufficient overlap of the data points. The procedure included a burial of the shot under perhaps six to eight inches of fine material, containing as much energy as possible in the ground. Some of the shots, however, did show a serious loss of energy into the air, resulting in poor seismic wave amplitude at the distant stations. A problem encountered in running refraction lines on the alluvium was difficulty in burying the shot in the often very coarse gravels. Under these conditions, it is suggested either to bury the shot deeper in order to get better coupling with the earth, or use more explosives as a surface charge.

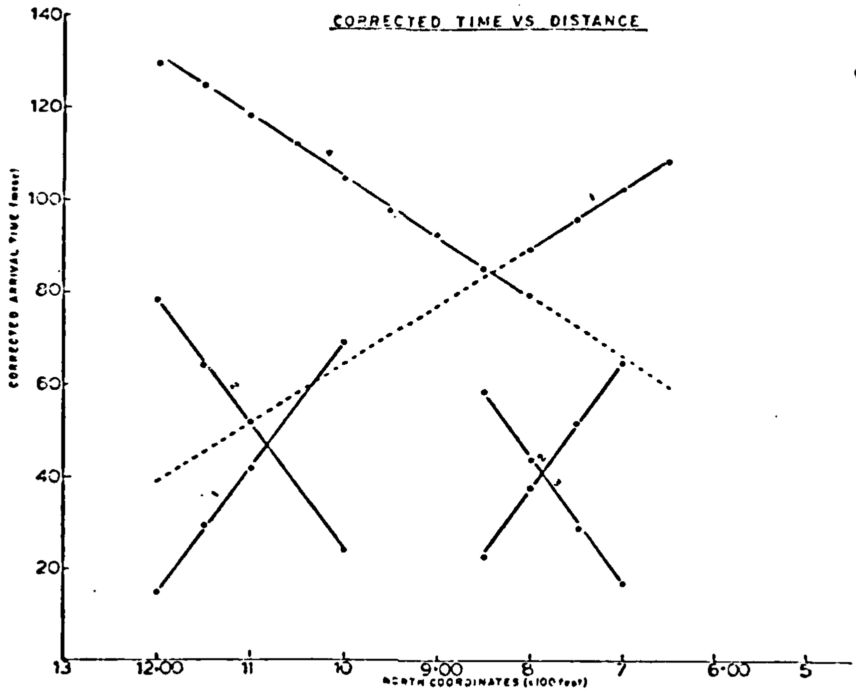
VI. Interpretation procedures and considerations

A. Plotting data

Time-distance plots were created from the data for each seismic traverse. The reciprocal method was used in interpreting the data, because it is one of the more general yet rapid interpretation methods available. Details of the intercept method can be found in the next section of this report. The velocities of the various subsurface layers are computed by fitting lines through the modified times on the time-distance graphs (Figure 11).

Corrected arrival times, T and Delay times, t (msec)	T_2	70.2	64.0	51.1	24.3	[illegible]	T_3	30.4	41.7	28.9	17.5
	T_1'	14.9	29.1	41.7	69.1	(64.9)	T_2'	23.5	36.1	52.9	64.7
	t_1	8.3	8.1	8.3	5.4	(1.9)	t_1	4.9	8.2	4.5	4.5
	T_4'	129.4	120.6	118.0	104.9	97.8		85.2	79.3	(72.9)	(66.2)
	T_1''	(39.2)	(40.0)	(50.5)	(63.6)	(70.8)		(83.3)	87.3	95.7	102.4
	t_{12}	(31.8)	(33.3)	(33.1)	(32.9)	(32.5)		(32.6)	33.0	(32.0)	(33.3)
Depths, Z (feet)	Z_1	12.9	12.5	17.0	11.1	(13.5)		12.1	10.7	10.1	9.2
	Z_2	(106.)	(113.)	(102.)	(115.)	(129.)		(111.)	116.	(117.)	(121.)

CORRECTED TIME VS DISTANCE



TRAVEL TIME VS. DIST NCE

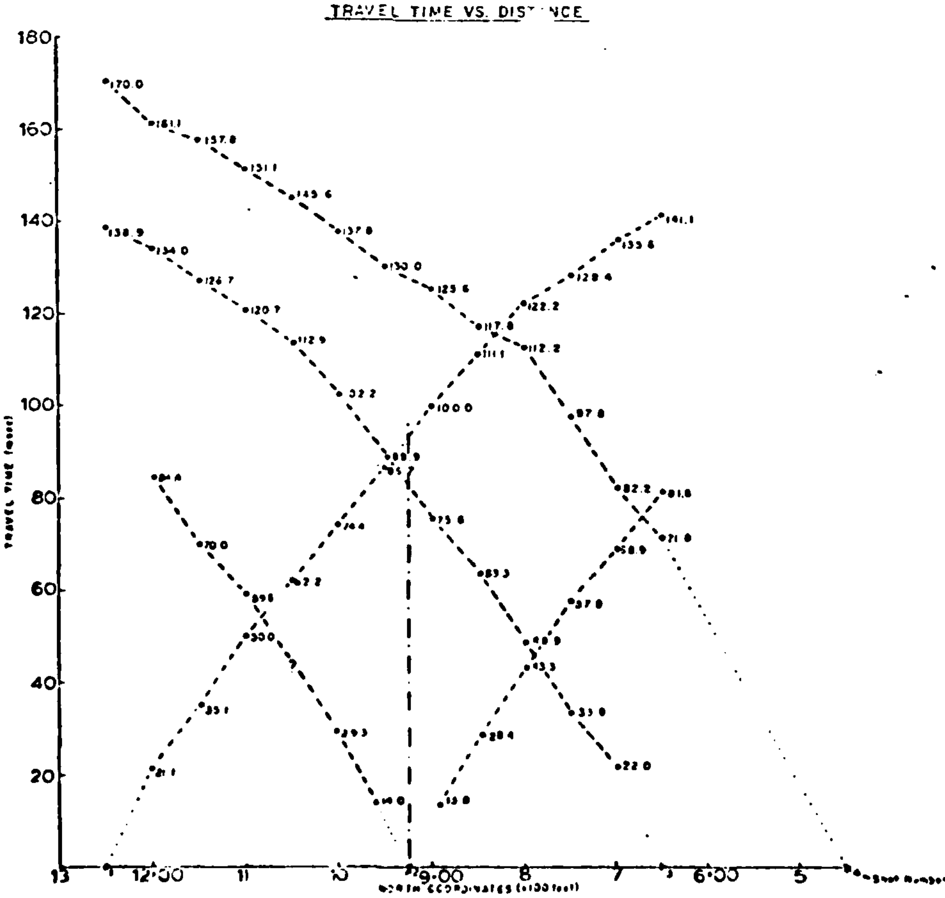


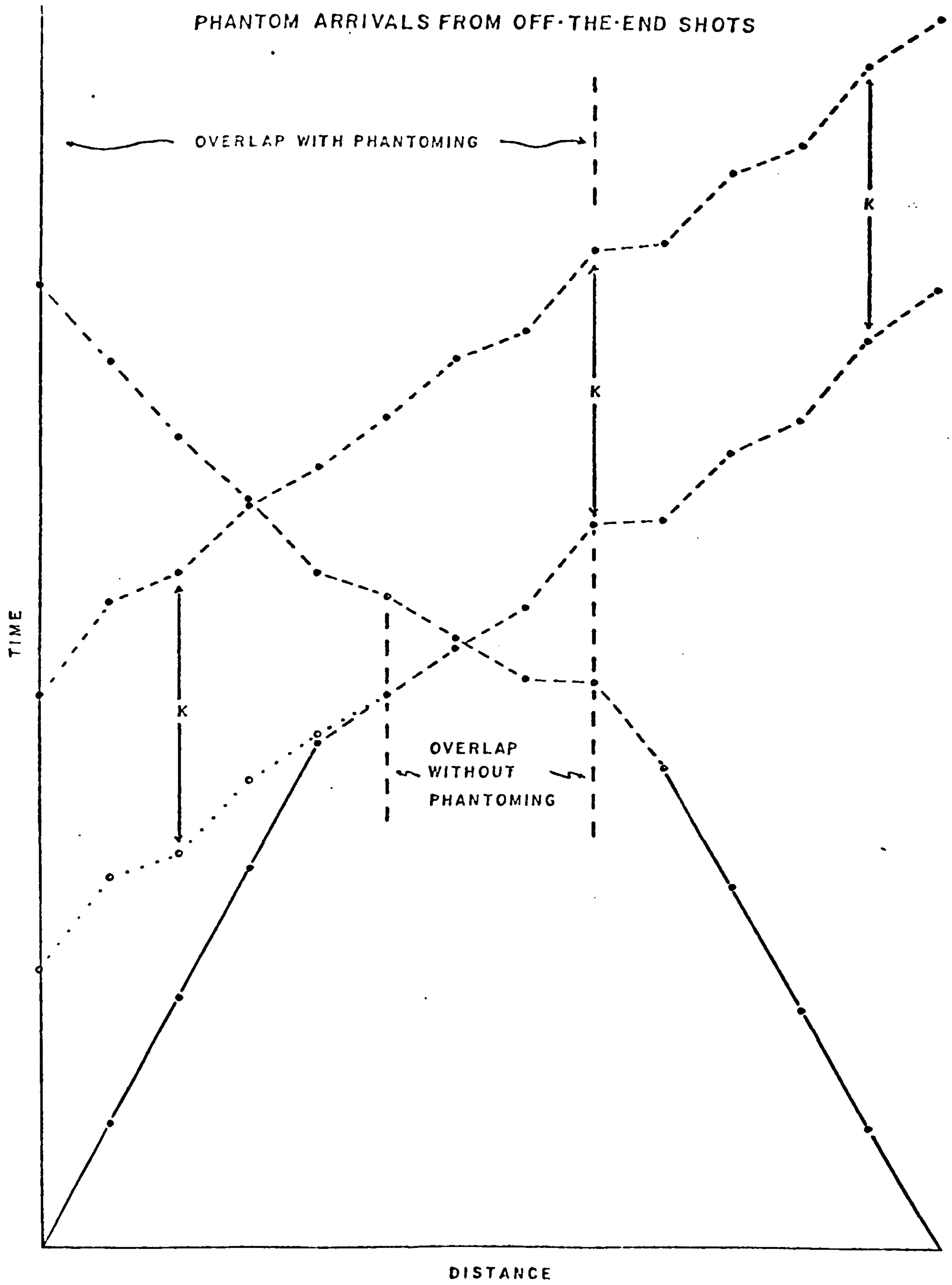
FIGURE 11

B. Computing delay times

The next step is to compute delay times for each station which has arrivals from both directions of shooting. Careful attention must be paid to the fact that the delay time is not a meaningful quantity unless it is calculated properly (Greenhalgh and Whiteley, 1977). That is, the interpreter must be sure that the arrivals in question are from the same refractor from both directions of shooting. If the arrival in consideration is from a particular refractor, an indicator is the corrected arrival vs. distance plots. Examination of these arrivals will determine if they fall in a straight line with adjacent arrivals which is thought to come from a certain refractor. In particular, the shotpoint-to-shotpoint time must be shown to be from the same refractor as the arrival at a particular geophone where the delay time is calculated. In some circumstances where this is not easily shot in the field, the end-to-end time may be computed by phantoming from adjacent lines along the same section (Figure 12).

C. Computing thicknesses

Once delay times and velocities for the different layers are known, a simple multiplication will yield the thickness of the layer in question. It must be borne in mind that the thicknesses computed are normal to the interfaces of the layers. When constructing a cross-section



(After Redpath 1973)

FIGURE 12

to interpret the geology of the area, these thicknesses should be scaled off as circular arcs below the geophone station. By connecting tangent lines to the arcs, the boundaries of the different layers can then be constructed.

D. Interpretation

In general, a three-layer model was constructed to interpret the data from the site, although the earth materials of the different layers most likely vary little from each other. Most of the materials at the site are sandy and clayey gravels, the difference between the layers being the degree to which they are saturated and compacted. For the surface layer we assume a compressional wave velocity of approximately 1,000 fps (300 mps). This material comprises mostly sands with some intermixed coarse gravels and a small fraction of clays and silts. It is typically unconsolidated and loose underfoot. The thickness of this first layer ranges from about 8 to 10 ft (2.5 to 3.0 m), up to 20 ft (6 m) across the survey area. It is assumed that this layer is undersaturated or dry in most cases, because of the arid climate, infrequent rains during the survey period and the general appearance of the site. The second layer has a velocity which varies across the spread between 3,800 and 4,100 ft per second (1,160 - 1,250 mps). The thickness of this layer was determined in the southern one-quarter of the test site to be about 100 to 120 ft (30 to 37 m). Because of the low velocity of the waves through this material, the spread was not long enough to pick up arrivals from the third layer. Thus, the thickness of the second layer over most the area is indeterminate. The third seismic layer at the test site was found to be about 7,800 to 8,000 fps (2,380 to 2,440 mps) in velocity. By combining the thickness of the first and second layer, where we see the signals from the third layer appearing, we can calculate that the third layer is approximately 120 to 130 ft (37 to 40 m) deep. This third layer is of a higher speed than the second layer because of a compositional difference, or because the materials at that depth are more compacted than the shallower clays, sands and gravels. More relevant to this study, however, the higher speed may be due to saturation of the gravel at this depth. In a routine groundwater investigation, the third seismic layer would be suspected of being the depth of the water table. When used with another method, such as electrical resistivity, the resisitivity survey would be designed knowing that the depth of interest is at about 130 ft (40 m). By using two methods in this manner, one can better define the subsurface groundwater regime.

VII. Example data reduction

A. The reciprocal method

This section will outline the reciprocol seismic refraction interpretation method. Two very good references regarding this method are Greenhalgh and Whiteley (1977), and Redpath (1973). The reciprocal method uses a quantity called the delay-time, which represents the time a wave would take to travel upward from a particular layer to the surface. The wave is defined as travelling normal to the interface, so the depths calculated are perpendicular distances. Using the delay time and the corrected travel time (equations 9 and 11 of Greenhalgh and Whiteley (1977) or equations 14 and 16 of Redpath (1973) one can plot the corrected arrivals vs. distance and calculate the true velocities of the various layers. Knowing the delay times and the true velocities, the depths to the layers of interest can be readily computed. It would be wise to caution here that all the refracted arrivals must be from the same layer, including the total end to end travel time, in any single delay time calculation.

B. Geologic setting

The geology at the site comprises alluvial gravels, sands, and clays compacted and saturated to varying degrees. This alluvium is reportedly several hundreds to thousands of feet (meters) deep on the east side of the valley. (Oral Comm., Dr. R. Hamilton, Colorado School of Mines, May, 1981.) Consequently, we may expect to see velocity contrasts based largely on degree of compaction and water saturation, rather than differences in rock type. One exception to this generalization is the known existence of clay rich lenses interbedded with the alluvium.

C. Data

The data shot at the site are presented in Figure 10. Curves of arrival time in milliseconds (msec.) versus distance in stations of one hundred ft are shown in the lower graph. The data show two prominent velocity layers upon first inspection. (By looking down a line of arrivals on a graph, with a small angle between your line of sight and the plane of the paper, departures from a straight line are more easily observed.) The next step in the interpretation is to calculate delay times and corrected arrival times for particular stations which show good overlap. This is done with several sample values in the table at the top of Figure 11.

D. Estimating velocities

As can be seen with the data from the deepest refractor, (arrivals from shot 4, between stations 8+00 and 12+00, and those from shot 1, between 8+00 and 6+50), overlapping arrivals only occur at one place, namely station 8+00. In this case, the true refractor velocity is estimated from the equation

$$V = \frac{2V_A V_B}{V_A + V_B}$$

where V is the true velocity and V_A , V_B are the apparent velocities, observed by fitting lines through the arrivals believed to be from the same refractor.

E. Corrected arrival times and thicknesses

Once the delay times and corrected arrivals are known, these arrivals are plotted on a graph, which appears above the travel time curves in Figure 12. The slopes of the corrected-arrival versus distance graphs should be equal for both directions of shooting over some specified interval. This provides a check on the accuracy of the data, and ensures whether a certain arrival is actually from the assumed refractor. The inverse slopes of the corrected arrival curves are equal to the true velocity in that layer, and are used in computing thicknesses. Knowing the true velocities and the delay-times, thicknesses are calculated as follows:

$$Z_1 = T_1 V_{1,2}$$

$$Z_2 = (T_2 - Z_1/V_{1,3}) V_{2,3}$$

where Z_1 , Z_2 are the first and second layer thicknesses T_1, T_2 are the delay times for those layers at some geo phone station, and

$$V_{A,B} = V_A V_B / (V_B^2 - V_A^2)^{1/2}$$

with V_B larger than V_A . Note that the delay time measured from the graph for the second layer, is the combined time for the seismic wave to travel up through the first two layers. This is why the equation for Z_2 has a quantity subtracted from the total delay time, T_2 . As mentioned before, the thicknesses are scaled off as arcs below each geophone station. The cross-section is then constructed by drawing envelopes which contain the tangents to the various arcs.

F. Geologic model

In interpreting the data, one must determine what geologic model corresponds to the travel-time curves. Various constraints can be put on the model right at the field site. For example, if bedrock outcrops are observed in the vicinity of the seismic line, any interpretation which yielded overburden thicknesses of 40 to 50 ft (12 to 15 m) would be questioned. Geologic maps (if any) and a table of average velocities such as the one in Heiland (1963) should also be used in constraining the model used to interpret the data.

G. Groundwater exploration

The most likely application of reconnaissance seismic refraction surveys in groundwater exploration is a detection of saturated zones which are of sufficient thickness and velocity contrast as to make them seismically visible. It is unlikely that thin saturated zones at great depth will be detected at all. If the operator has sufficient experience, and the refraction survey has good data overlap, an advanced reduction scheme such as the Generalized Reciprocal Method (Palmer, 1980), may be used, allowing more subtle saturated zones to be found. These would include thin layers which are prone to a blind zone condition, and possibly indirect detection of zones with inverted velocities. Most likely, a small computer and digital data recording would be utilized in this regard.

The seismic refraction survey then, should be used in conjunction with other geophysical prospecting tools such as resistivity, self-potential, and electromagnetic methods. The integration of several exploration methods increases the constraints on the problem, increasing the reliability of the interpretation.

Appendix C - Guide for the Use of the DC Resistivity Method for the Detection of Groundwater

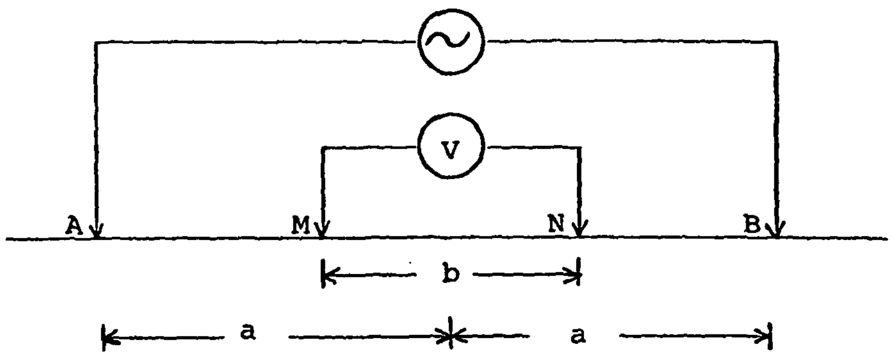
I. Theory of the method

A. Current flow

The DC resistivity method assumes when current is introduced into the ground, its flow through the earth is dictated by the physical properties of various rock layers within the earth. The current flow is different in the surface measuring circuit if the physical properties of the various layers change. The important physical properties include the resistivity of individual layers and their thicknesses. In effect, it might be thought of as having a series of parallel resistors in which one is measuring the voltage across one resistor (surface resistor) and when additional resistors are added in parallel, one notices changes in the voltage drop through the surface resistor. This is an excellent analogy to the effect of additional layers on the measured potentials. By expanding the current electrode spacing in the DC method, one is generally forcing the current to flow through other units in the subsurface and, hence, one observes the effect of current flow in these additional units on the measured potential at the surface. Fundamentally, the increase in the electrode spacing (usually the energizing electrodes) allows one to investigate deeper and deeper within the earth. The measuring electrodes are usually held at a fixed spacing while the outer electrodes (current electrodes) are expanded. However, reciprocity tells us that we can use the outer electrodes as potential electrodes and the inner electrodes as current electrodes and achieve the same results.

B. Interpretation schemes

Generally, the measured apparent voltage at the potential electrodes is used in conjunction with the input current to compute an apparent resistivity based on the geometric factor for the electrode spacing. The geometric factor is derived by determining the potential at each measuring electrode from each of the current electrodes. Then, these two potentials are summed to yield the net effect of the two current electrodes. This relationship is shown in Figure 13 (modified from Keller and Frischknecht, 1966). Using this equation, one can derive a geometric factor to be included in the calculation of the apparent resistivity for each spacing of the electrodes. Thus, the apparent resistivity, the principal quantity of interest, is calculated from the measured potential at the measuring electrodes, the input current and the electrode configuration (the geometric factor). Standard interpretation schemes require one to compute the resistivity at various electrode spacings. These apparent resistivity values are plotted as a function of the electrode spacing which is



The geometric factor: $k = \pi\left(\frac{a^2}{b} - \frac{b}{4}\right)$

$\rho_a = k \frac{\Delta U}{I}$

where ΔU is the measured potential
I is the input current
ρ_a is the apparent resistivity

(After Keller and Frischknecht, 1966)

Figure 13

Schlumberger DC Resistivity and
Fundamental Equations

then assumed to relate to the depth of investigation. Commonly, these measurements are plotted on a log-log plot of apparent resistivity versus one-half of the current electrode spacing. This format is common for the Schlumberger array which was used during the field experiments. There are a number of other electrode configurations and an appropriate geometric factor can be computed for any configuration.

C. Relationship to groundwater

In most instances that would be encountered in groundwater exploration, the principal mode of current transport is through the fluid in the pore spaces of the rock. A commonly used relationship between the apparent resistivity of the rock (ρa), the porosity ($\emptyset$), the resistivity of the water (ρ_w), and saturation (Sw) is given below. M and N are exponents that vary with certain parameters. A value of two is typical for these exponents.

$$\rho a = \rho w \emptyset^{-M} Sw^{-N}$$

This equation allows one to determine the water saturation for measured apparent resistivities, if one knew the water reisitivity and the porosity of the rock. However, for most cases, these are also unknowns forcing one to look at relative resistivities and attempt to relate them to saturation and porosity. Therefore, in groundwater exploration, one attempts to map low resistivity zones. The characteristics of these zones and a knowledge of the local geology allows one to semi-quantitatively assess the groundwater potential.

II. Problems and limitations of the method

A. Geometric problems

All of the assumptions for interpreting resistivity data are based on the current flowing through horizontally layered beds within the influence area of the energizing and measuring electrodes. Extreme deviations from these assumptions create significant problems with the data and complications in its interpretation. For example, steep dips in the area and even the outcrop of some units when the electrodes extend beyond these areas will greatly influence the data, contaminating the results.

The effect of lateral changes in resistivity, either through dip or through changes in rock type significantly alters the results. The method does not indicate these lateral changes, but rather averages large volumes of earth. Consequently, even significant structure changes as an intrusive, or a basement fault, etc., will not be directly indicated in the data, but instead will cause distortions in the data that will force one to make interpretations of average depth and average properties.

B. Resistivity contrast

Another problem is a lack of discrete resistivity changes within the section. In other words, if the resistivity does not vary from layer to layer at discrete boundaries, then the DC resistivity method is not useful for defining the physical properties or extent of individual layers. Rather, one sees a more or less homogeneous resistivity for the interval which does not allow the resolution of individual layers.

C. Conductive zones

The occurrence of a relatively thick near-surface conductive zone greatly contaminates the results in resistivity surveying. In effect, it acts very much like the blind zone in refraction surveying and a concentration zone for all the electrical current. In other words, a shallow conductive zone allows most of the current to flow through this zone and very little current to penetrate below it discouraging efforts to resolve the units below the conductor. The DC resistivity method is most useful for defining depths to resistive layers. Also, one can use it in many cases to resolve [illegible]s of fluid saturated rocks at depth. However, if there is a shallow water-bearing unit, oftentimes it is impossible to resolve any deeper units. This is one argument for going to the electromagnetic exploration methods where one may be able to resolve conductors at depth.

III. Available equipment

A. State-of-the-art

The state-of-the-art in portable DC resistivity equipment has progressed quickly within the last few years. The instrumentation uses similar chips that are being used in hand-held calculators and other portable electronic devices. Even without new research and development efforts, DC resistivity systems can be purchased which are light-weight and reliable under typical field conditions. However, this does not preclude bringing spare parts and maintenance gear to the field. Like any system that uses electronic components, it is best if one avoids exposure to extreme variations in temperature, moisture and weather.

B. Averaging resistivity systems

Several DC resistivity systems use a summing device to allow operation in noisy environments where electronic signals may hinder and handicap measurements of the appropriate signal levels. These devices operate in a manner similar to signal enhancement seismographs whereby they utilize the zero crossings to sum the data to increase the signal-to-noise ratio. These devices operate off a clock that, in effect, counts the cycles so that they are always summing the same polarity signals. Therefore, these instruments require sophisticated timing devices. Such devices are sometimes susceptible to field problems. Experience with two different kinds of these instruments has indicated varying degrees of reliability in adverse field conditions. One set of instrumentation was extremely reliable in the field, very portable and operated under extremely adverse conditions. The second set of instrumentation had extreme difficulty in the field, broke many times and appeared to be adversely affected by the environmental problems. However, it was more powerful and potentially more useful than the other device. The manufacturer of the second device has indicated that they have since corrected those problems with electronic failures.

C. Non-summing DC resistivity systems

Another way to ensure that one can gather resistivity data from great off-sets is to utilize more power and thus raise the signal-to-noise ratio through the use of a larger signal. These devices, as currently available on the market, are limited in their depth investigation because of power constraints if portability is maintained. This implies that a summing device has certain advantages over a straight single shot device. Both sets of instruments currently available using these approaches generally display their signal on LCD displays that allow for easy reading and eliminate many of the potential errors in reading meters and multiplying by multiplier scales, etc. Thus, the ease of operation in the field is very good.

D. Representative equipment

There are a number of systems available. Several systems are made by Bison Instrument Company of Minneapolis, Minnesota. They make both devices that are single pulse devices and devices with signal averaging capability. Their signal averaging device has good capability, but we have experienced operational difficulties. Their single pulse equipment is an extremely reliable device that is good for investigations to a couple of hundred feet (70 m). ABEM, a Swedish company, makes a device called a Terrameter that also uses a signal averaging approach and is an extremely reliale instrument. However, its depth capability without a power booster is not as good as the Bison instrumentation.

IV. Field procedures

A. Equipment deployment

A typical field layout for groundwater exploration would include a portable summing resistivity system, electrodes, wire, and measuring tapes (Figure 14).

B. Areal considerations

The strategy would be to locate a series of station locations about which to expand the surface array. The data need not be acquired in a continuous fashion, because each sounding would be sampling a large portion of the area and there would be no necessity for overlap.

C. Common practices

Common practices would be to begin with both source and current electrodes very closely spaced. This would involve a potential measuring electrode spacing of approximately 3 ft (1 m) and a current electrode spacing of approximately 10 ft (3 m). One would then expand the electrode spacing for the current electrodes in a symmetrical manner about the mid-point. The plotted spacing would be from the center of the measuring electrodes to one current electrode. The expansion should be logorithmically. In other words, one need not take equal spaced electrode measurements all along the

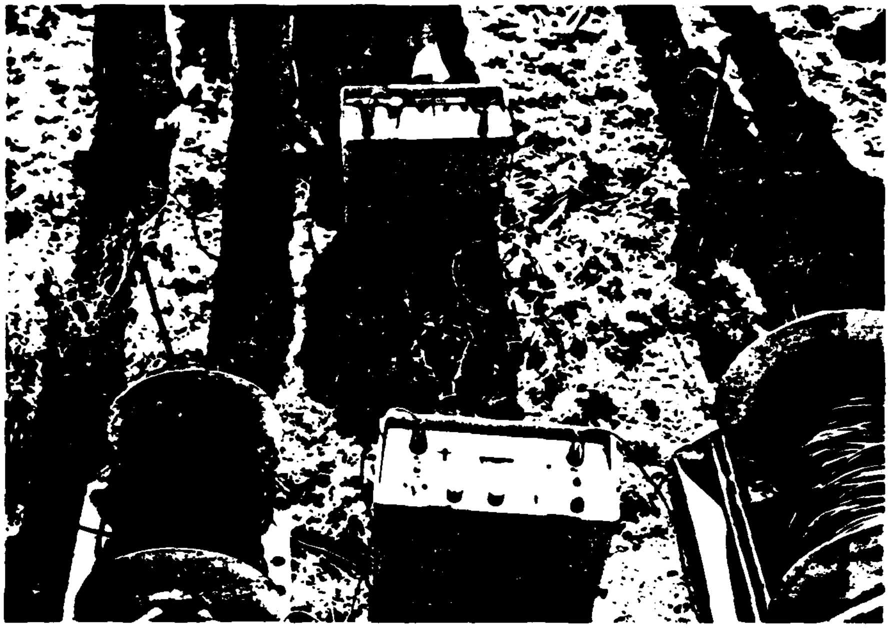


Figure 14. Groundwater exploration equipment: DC resistivity.

line. Rather, one would attempt to space the electrodes so that one gains information from multiple depths without redundancy of data. For example, it may be valid to make measurements at current electrode spacings of 20 ft (6 m), 35 ft (11 m), 50 ft (15 m), 80 ft (24 m) and 120 ft (36 m), but it is not required to make measurements at 220 ft (67 m), 230 ft (70 m), 240 ft (73 m), rather it is probably appropriate to make measurements at spacings of 200 ft (60 m), 350 ft (110 m), etc. One can look at a sheet of log-log paper and choose appropriate intervals to end up with a logically sampled set of data. The field work is easily carried out with a man at each of the current electrodes and one man with the instruments at the measuring electrodes. This individual tells the others when to move out to the next station. They move out to that station and hammer in the current electrodes. In order to go to the appropriate station spacing, one should use a tape (non-mettallic) stretched out in each direction. This minimizes the moving of items back and forth. In fact, if one did not want to force a reading of the tape (for the station position), one could lay out a tape with the stations premarked as A, B, C, D, E, etc. Three men can make a resistivity sounding to an AB/2 spacing of 1000 ft (300 m) in approximately 45 minutes. Therefore, a group, counting moveup time, could average 8 to 10 lines per day. Making shallower measurements to AB/2 spacings of 300 ft (91 m), greatly expedites the work and approximately 30 measurements per day are possible.

V. Field DC resistivity soundings

A. Summary

Electrical resistivity soundings were conducted at two sites on the eastern side of the San Luis Valley in south-central Colorado. These two sites were in areas where both SP and refraction measurements were also made. The objective was to determine if saturated alluvial (gravel) layers existed in the area and could be detected using DC resistivity methods. One sounding was taken near a well in which groundwater was at a depth of approximately 70 ft (21 m) and the other sounding was taken further out in the valley. The data in both areas were acquired using the Schlumberger field procedure in which the current electrodes are expanded while the measuring electrodes are held constant. The spacing between the current electrodes is much larger than the spacing between the potential electrodes. The apparent resistivity was calculated from each of the measurements and plotted as a function of electrode spacing which is a function of depth. From this data, a relationship was interpreted between the apparent resistivities and the thicknesses of the various layers. There are a number of interpretation procedures that can be used in interpreting DC resistivity data in a quick fashion. These include a curve matching interpretation in which one uses characteris-

tic curves based on relative resistivities to assess the resistivity and thicknesses of discrete layers. The asymptotic method of interpretation is useful for only two layer cases in which one estimates the depth to the second layer. For this method of interpretation, one assumes that the second layer is either infinitly more conductive or infinitely more resistive than the first layer. A third manner of interpreting DC resistivity data is to use a computerized inversion method. This method computes in an iterative fashion, the "best fit" resistivities and thicknesses for discrete layers. While the inversion method is desirable in terms of consistency and ease of operation, it also can make many of the standard errors that are inherent in computer interpretation, such as honoring all points of data. Therefore, it is suggested that, even if inversion methods are used, one still plot the data by hand, look at the general shape of the curve and evaluate the results as a check. Curve matching requires more experience than does the computerized inversion method, but it does offer good reliability for up to three layers.

B. Sample Data

The two curves for the two sets of data show different results. Spanish Camp data was acquired near a stream and a well. This well, water depth, 70 ft (21 m) was within 100 ft (30 m) of the stream and, hence, probably showed a cone of infiltration into the deeper strata. The data derived from this curve (Figure 15) shows a very resistive, 6.6 ft (2 m) thick near-surface layer of 5,100 ohm-ft resistivity; a second layer about 44 ft (13 m) thick with an apparent resistivity of 600 ohm-ft; a third layer with an apparent resistivity of 2,700 ohm-ft, about 60 ft (18 m) thick; and a fourth layer at a depth of 110 ft (33 m) with a resistivity of 810 ohm-ft. Figure 16 shows graphically the section. Obviously, the near surface layer is dry, and the third layer also appears to be relatively dry. The second layer may be partially saturated from seepage from the stream. The fourth layer may be the aquifer that is being recharged by the stream, especially in light of the additional data from the other surveys. Road CC is off the alluvial fan closer to the center of the valley. This curve (Figure 15) shows a near-surface layer approximately 2 ft (1 m) thick with 210 ohm-ft resistivity; a second layer, apparent resistivity of 1,600 ohm-ft, 36 ft (11 m) thick; and a third layer at 38 ft (11.5 m) depth and 230 ohm-ft apparent resistivity. Figure 16 summarizes this data. The near-surface layer is partially saturated because of the irrigation in the immediate vicinity. The second layer is probably relatively dry alluvium, while the third layer is the aquifer. The two curves do not

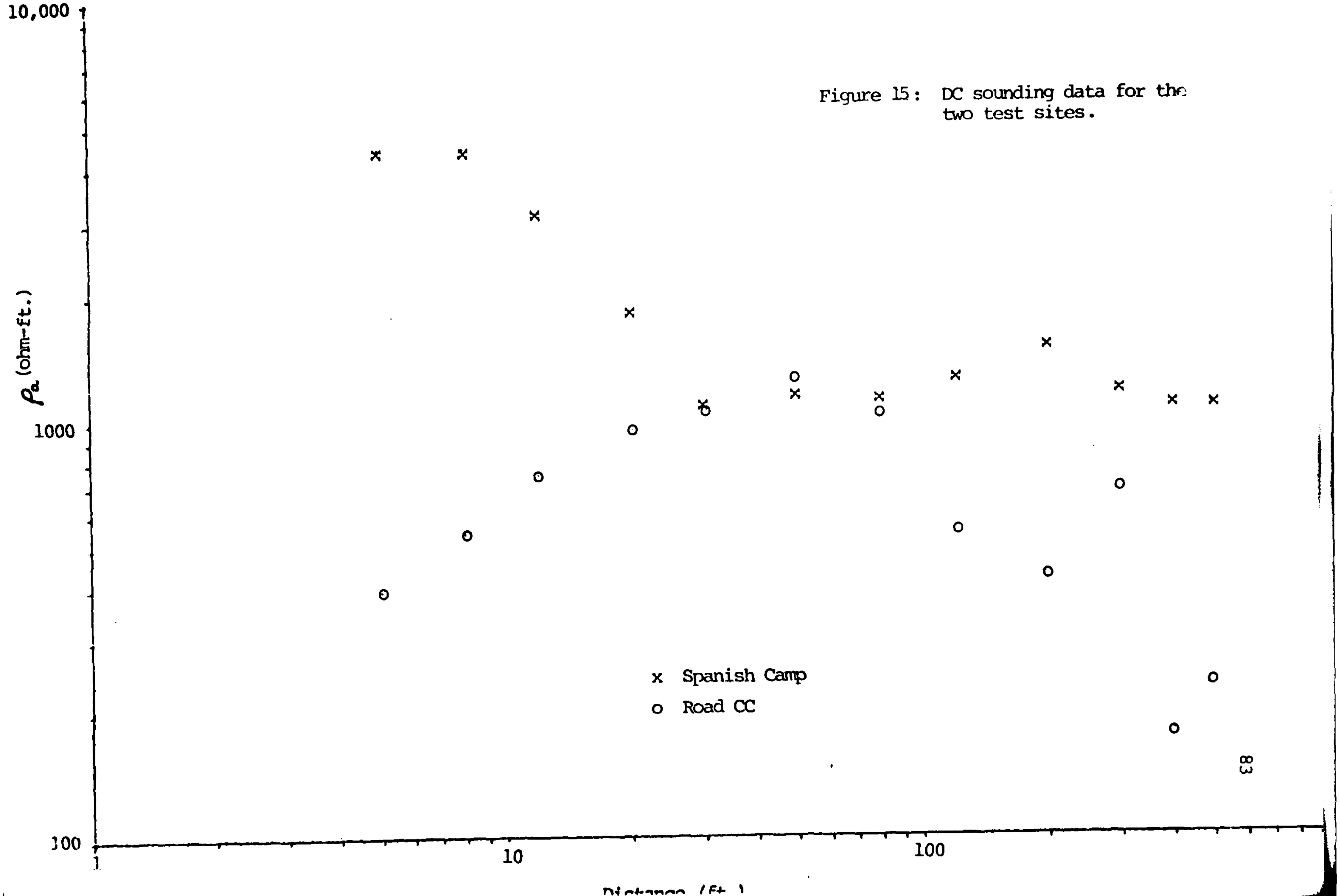


Figure 15: DC sounding data for the two test sites.

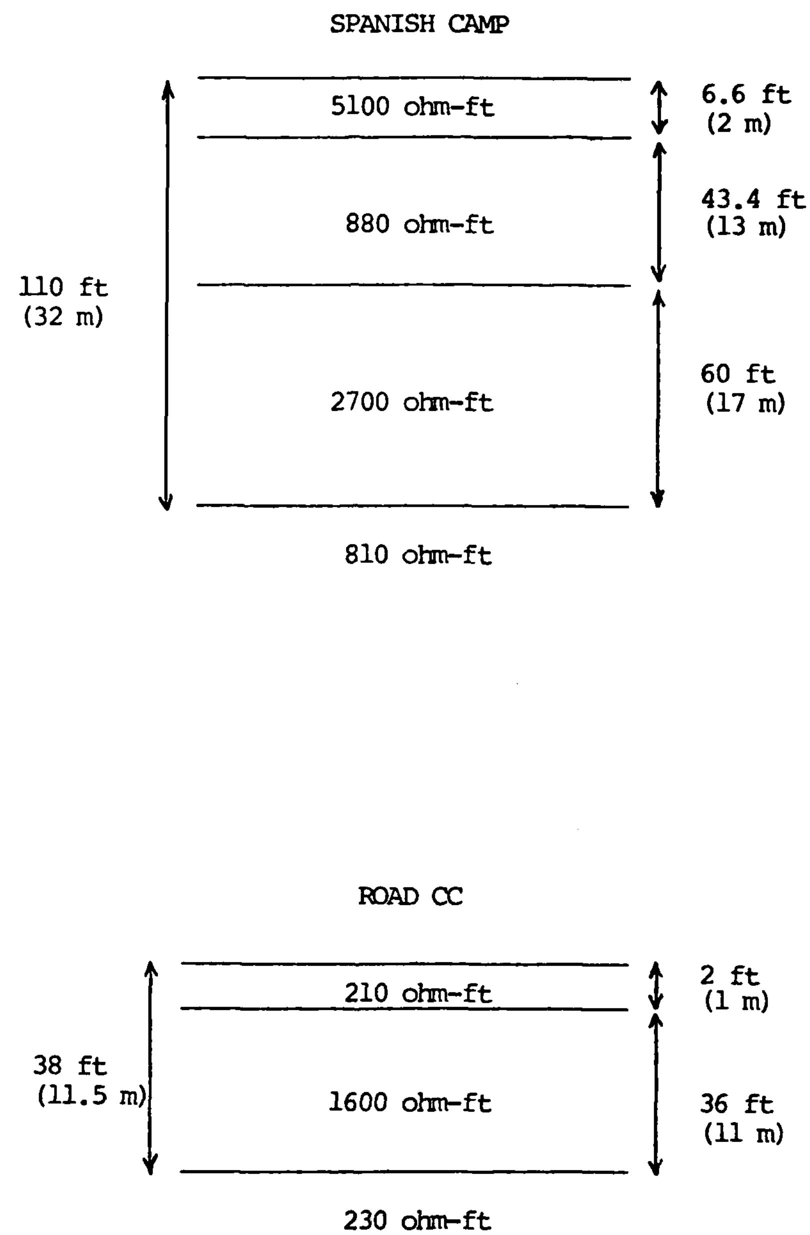


Figure 16: Geoelectric sections for the two test sites.

definitively resolve the aquifer but, when coupled with a knowledge of the geology, suggest that one would have to drill deeper to find water at Spanish Camp than in the middle of the valley. This may be because there is less alluvial cover over the aquifer in the center of the valley than on the fan. These data are more conclusive when coupled with the results from the SP and the refraction surveys. However, a knowledge of the geology is extremely important in interpreting this data.

VI. References

The references available on electrical exploration methods are quite extensive. Many were reviewed for this study. A principal electrical reference is a book by Keller and Frischknecht, 1966. Other pertinent literature available includes a report by Emilia et al (1976), written as a guide to groundwater exploration in Ethiopia. These publications and many additional publications clearly illustrate the principles of the electrical methods. These references provide the theoretical background, operational methods and general interpretation schemes. More detailed references are in geophysical publications such as Geophysics, a publication of the Society of Exploration Geophysicists, and Geophysical Prospecting, a publication of the European Association of Exploration Geophysicists. In addition, there are special publications by both organizations that relate to the exploration for groundwater. Also, there are a number of other specialized journals that treat these problems. Many of these groundwater articles are case history oriented.

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Glossary

absolute value: The numerical value when direction or sign is not considered.

alunite: A mineral usually in white, gray or pink masses in hydrothermally altered feldspathic rocks.

analog: Continuous, as opposed to discrete or digital.

anomaly: A deviation from uniformity.

apparent resistivity: The ground resistivity calculated from measurements and a geometric factor derived for the case where the ground is homogeneous and isotropic.

acquifer: A saturated permeable geologic unit that can transmit significant quantities of water under ordinary hydraulic gradients.

centi: A prefix meaning ten raised to the power of - 2. Symbol c.

coal burn: A zone within a coal seam undergoing spontaneous combustion under the earth's surface.

conductivity: The ability of a material to conduct electrical current. In isotropic material, conductivity is the reciprocal of resistivity.

current: The flow or rate of flow of electric force in a conductor, from a point of higher potential to one of lower potential.

detritus: The material produced by the disintegration and weathering of rocks that has been moved from its site of origin.

drift: A gradual and unintentional change in the reference value with respect to which measurements are made.

electrode: A piece of metallic material that is used as an electrical contact with a non-metal.

electrolyte: A material in which the flow of electric current is accompanied by the movement of matter in the form of ions.

fault: A displacement of rocks along a shear surface.

fissure: An extensive crack, break, or fracture in the rocks.

geologic contact: The place or surface where two different kinds of rocks come together.

geothermal energy: The internal energy of the earth, available to man as heat from heated rocks, water, etc.

gradient: Change in value of one variable with respect to another variable, especially vertical or horizontal distance.

groundwater: That part of the subsurface water which is in the zone of saturation in soils and geologic formations.

hydraulic gradient: The rate of change of pressure head per unit of distance of flow at a given point and in a given direction.

input resistance: The impedance across the input terminal of an electrical circuit.

ion: An electrically charged atom or group of atoms.

kilo: A prefix meaning ten raised to the power of 3. Symbol k.

mega: A prefix meaning ten raised to the power of 6. Symbol M.

meter: A unit of length equivalent in the United States to 39.37 inches exactly.

milli: A prefix meaning ten raised to the power of - 3. Symbol m.

mV/mi: Millivolts per mile. For every mile of line in the SP survey, some quantity of millivolts is acquired.

mineral deposit: Any valuable mass of ore.

ohm: A unit of electrical resistance or impedance; a resistance or impedance of one ohm has a potential drop across it of one volt per ampere of current.

parameter: Quantities (each of which may represent a combination of quantities) which are sufficient to determine the response characteristics of a system.

pegmatite: Those igneous rocks of coarse grain found usually as dikes associated with a large mass of plutonic rock of finer grain size.

period: The time for one cycle. The time for a wavecrest to traverse a distance equal to one wavelength.

permeable: Having a texture that permits water to move through it perceptibly under the head differences ordinarily found in subsurface water.

polarization: The occurence of electrodes becoming electrically positive or negative.

porous: Containing voids, pores, or other openings which may or may not interconnect.

potential: Electrical voltage with respect to a reference point.

resistivity: The property of a material which resists the flow of electrical current. The reciprocal of resistivity is conductivity.

silicification: The introduction of or replacement by, silica. Generally the silica formed is fine-grained quartz, chalcedony, or opal, and may both fill up pores and replace existing minerals. The term covers all varieties of such processes, whether late magmatic, hydrothermal or diagenetic.

substructure: The structure of geology beneath the surface of the earth.

subsurface: The zone of geology beneath the surface of the earth.

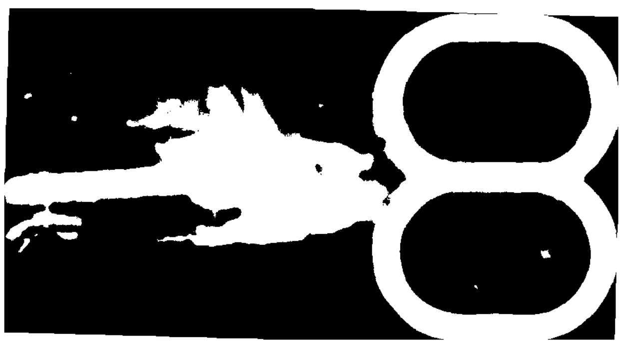
telluric current: A natural electrical earth current of very low frequency which extends over large regions and may vary cyclically in that direction. Telluric currents are widespread, originating in variations of the earth's magnetic field.

temporal: Of or limited by time.

topography: The physical features of a region, such as are represented on maps; especially, the relief and contour of the land.

wavelength: The distance between successive similar points on two adjacent cycles of a monochromatic wave, measured perpendicular to the wavefront.

weathering: The group of processes, such as the chemical action of air and rain water and of plants and bacteria and the mechanical action of changes of temperature, whereby rocks on exposure to the weather change in character, decay, and finally crumble into soil.


8